Eruption Dynamics and Petrology of the Most Recent Eruptions of Nevado Del Ruiz Volcano, Colombia, South America

Richard Henry Young

Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Part of the Earth Sciences Commons

Recommended Citation

https://digitalcommons.lsu.edu/gradschool_disstheses/8231

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
ERUPTION DYNAMICS AND PETROLOGY OF THE MOST RECENT ERUPTIONS OF NEVADO DEL RUIZ VOLCANO, COLOMBIA, SOUTH AMERICA

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in The Department of Geology and Geophysics

by
Richard Henry Young
A.S., McNeese State University
B.S., Louisiana State University
August 1991
MANUSCRIPT THESES

Unpublished theses submitted for the Master's and Doctor's Degrees and deposited in the Louisiana State University Libraries are available for inspection. Use of any thesis is limited by the rights of the author. Bibliographical references may be noted, but passages may not be copied unless the author has given permission. Credit must be given in subsequent written or published work.

A library which borrows this thesis for use by its clientele is expected to make sure that the borrower is aware of the above restrictions.

LOUISIANA STATE UNIVERSITY LIBRARIES
ACKNOWLEDGEMENTS

I would like to thank Stan Williams for his patient support and friendship through the course of this work. His infectious enthusiasm for his students and his work encouraged me to do things and go places I never would have imagined, had I not met him. All the strange situations and wild destinations will make great stories for years to come, and all those who spend time on the "volcano couch" will surely be subjected to them all. A special thanks also to Lynda Williams for her warm hospitality at the countless parties and meals she and Stan hosted in their home.

Thanks also to Gary Byerly and Darrell Henry for their input, direction, and reviews of this work as members of my thesis committee. Additional advice came from Bill Melson at the Smithsonian; Steve Nelson and Owen Mills of Tulane were very helpful with the XRF analyses. I would like to also thank the remainder of the staff of the LSU Department of Geology and Geophysics for the use of the facilities, especially Gary Lovell, for his valuable help with the microprobe. I also gratefully acknowledge the logistical support of the staff of the Observatorio Vulcanológico de Colombia in Manizales and INGEOMINAS.

Special thanks to the rest of the Stan Williams School of Volcanology students and alumni: Marta Lucia Calvache V., Nemesio Perez, Dina Lopez, Steve Schaefer, Dave Lescinsky, and Kirt Kempter. I also thank my family and friends for their support.

Funding for this project was provided by NSF grants # EAR-8721206 and INT 8714954. Additional funding came from Geological Society of America grant #4126-88.
# TABLE OF CONTENTS

Acknowledgements .................................................................................... ii
Table of Contents .................................................................................... iii
List of Tables ........................................................................................ iv
List of Figures ........................................................................................ v
Abstract ................................................................................................. vi
Introduction ............................................................................................ 1  
  Geological Setting ................................................................................ 1  
  Recent Activity ..................................................................................... 7  
  Scope and Purpose of the Study ............................................................ 10
Part One: Petrography and Petrology .................................................... 12  
  Samples and Analytical Methods ......................................................... 12  
  Petrographic Overview ........................................................................ 17  
  Mineral Chemistry ................................................................................ 25  
  Plagioclase .......................................................................................... 27  
  Orthopyroxene .................................................................................... 28  
  Clinopyroxene ..................................................................................... 32  
  Olivine ................................................................................................. 34  
  Whole Rock Analyses ........................................................................... 38  
  Major Elements ................................................................................... 50  
  Trace Elements .................................................................................... 50  
  Matrix Glass Chemistry and Magma Water Content Estimates ....... 52  
  Discussion- Petrogenesis of the Ruiz Pumices .................................. 66
Part Two: Eruption Dynamics ................................................................. 74  
  Introduction .......................................................................................... 74  
  Field Methods and Analytical Procedures ......................................... 74  
  Volumes ............................................................................................... 75  
  Column Heights .................................................................................. 78  
  Eruption Classification ........................................................................ 79  
  Discussion of Ruiz Eruption Dynamics ............................................... 85  
  Conclusions ........................................................................................ 92
References ............................................................................................... 94
Appendix 1: Microprobe Standards Calibration ..................................... 99
Appendix 2: Whole Rock Data Distributions ....................................... 102
Appendix 3: Isopach, Isopleth, and Median Grainsize Maps ............... 106
Vita .......................................................................................................... 121
LIST OF TABLES

Table 1  Olivine and Pyroxene Analyses .................................................. 31
Table 2  Iron-Titanium Oxide Analyses, Temperatures and Oxygen Fugacities . 36
Table 3  Whole Rock Analyses .................................................................... 39
Table 4  Matrix Glass Analyses .................................................................... 55
Table 5  Summary of Individual Eruption Dynamics ..................................... 81
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>View of Nevado del Ruiz Volcano</td>
</tr>
<tr>
<td>Figure 2</td>
<td>View of Nevado del Ruiz and Crater La Olleta</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Location Map of Nevado del Ruiz</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Proposed Caldera Boundary Fault</td>
</tr>
<tr>
<td>Figure 5</td>
<td>View of Ruiz Stratigraphy in Outcrop</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Idealized Stratigraphy and Radiocarbon Dates</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Pumice Types Erupted in 1985</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Typical Pumice in Thin Section</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Sieve-Textured Plagioclase</td>
</tr>
<tr>
<td>Figure 10</td>
<td>R6 Pumice in Thin Section</td>
</tr>
<tr>
<td>Figure 11</td>
<td>R0 White Pumice in Thin Section</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Resorbed Olivine Xenocryst in Thin Section</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Range of Pyroxene Compositions</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Pyroxene Core and Rim Compositions</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Zoning Patterns in Pyroxenes</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Whole Rock Harker Variation Diagrams</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Whole Rock Classification</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Silica Content Versus Time</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Whole Rock Distribution Compilation</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Plot of K2O vs. Rb</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Plot of FeO*/Mg vs. SiO2</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Plot of Rb vs. K/Rb</td>
</tr>
<tr>
<td>Figure 23</td>
<td>Magma Water Content Estimates</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Banded Pumice, Eruption R4</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Thickness vs. Area Plot, Eruption R8</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Column Height Determinations</td>
</tr>
<tr>
<td>Figure 27</td>
<td>VEI Determinations</td>
</tr>
<tr>
<td>Figure 28</td>
<td>Comparison to Other Plinian Dispersal Data</td>
</tr>
<tr>
<td>Figure 29</td>
<td>Classification of Eruptions Using the Scheme of Pyle, 1989</td>
</tr>
<tr>
<td>Figure 30</td>
<td>Cumulative Volume vs. Time</td>
</tr>
<tr>
<td>Figure 31</td>
<td>Cumulative Accumulation Isopach Map</td>
</tr>
</tbody>
</table>
ABSTRACT

Field measurements and petrographic analyses of pumices from the most recent tephra deposits of Nevado del Ruiz volcano provide a context in which to view the disastrous eruption of 13 November, 1985 (R0). The pumices are all crystal-rich, two-pyroxene andesites to dacites with whole rock SiO$_2$ contents of 62 - 66 wt.%, and magma water contents estimated to be between 1 - 4 wt.%. The 1985 tephra has greater petrologic diversity than earlier deposits which may be related to an input of a hotter, more basic magma into the Ruiz system, as suggested by xenocrystic olivine which is most abundant in the tephras of R1 (1845) and R0.

Maximum pumice and lithic isopleth maps were used to define dispersal axes, classify eruptive styles and estimate theoretical column heights. Isopach maps were used to estimate individual deposit volumes. Results indicate that the pre-1985 eruptions were less intense (lower column heights) than R0, but of greater magnitude (total volume), producing up to 15 times the volume of the 1985 deposit. R6 is petrographically and petrologically unique, and may have originated from a currently inactive crater. Calculated volumes for eruptions R8 - R0 range from 0.02 - 0.29 km$^3$ with estimated column heights of 18 -26 km. All eruptions, except R1 and R6, can be classified as plinian in nature.

A cumulative isopach map of the tephra layers from the active Arenas crater reveals that the deposits have accumulated in a nearly circular pattern around the volcano, which is slightly elongate along an axis directed S-SW from the summit. We propose that a revision of the current Ruiz ashfall hazard map is necessary, and should reflect a more balanced consideration of the distribution and volumes of the pre-1985 deposits.
INTRODUCTION

GEOLOGICAL SETTING

Nevado del Ruiz is a large, broad, glacier-capped stratovolcano located atop the Central Cordillera of the Northern Andes of west-central Colombia, approximately 135 km W-NW of Bogota' (Figures 1, 2, 3). The Ruiz-Tolima volcanic complex marks the Northern terminus of active Andean volcanism on the South American continent and includes Cerro Bravo volcano, which last erupted less than 300 years ago (Lescinsky, 1990). The Central Cordillera of the Northern Andes is separated from the Western and Eastern Cordilleras by the Cauca and Magdalena River valleys, respectively, and is situated approximately 200 km east of the Colombian Trench, where the Nazca plate is obliquely subducted beneath the western Colombian margin of the South American plate at a dip angle of 25-30° (Thorpe, 1984).

Divided between the departments (states) of Caldas and Tolima, the 5400 m volcano (4° 53' N, 75° 22' W) lies at the complex intersection of the inactive Paleozoic Palestina strike-slip fault (N20° E) with several groups of smaller, younger, active normal fault systems (Jaramillo, 1980; Thouret et al., 1990). The volcanic massif overlies a metamorphic basement of Paleozoic schists beneath Mesozoic volcanioclastic deposits which have been intruded by Jurassic and Paleogene granodioritic batholiths and stocks (McCourt et al., 1984). Jaramillo (1980) has reviewed the geology and tectonic evolution of the Northern Andes of Colombia. Briefly, the first of the two most recent orogenic cycles began about 1 billion years ago, when the northwestern core of the South American continent became the leading edge of a subduction zone and ended in the middle Paleozoic with the closing of the proto-Atlantic Ocean. The resulting collision between South America and the Panama Arc produced the ancestral Central and Eastern Cordilleras of Colombia. The second cycle, or Andean cycle was initiated in the Late Paleozoic. Uplift of continental crust along the strike of the present-day Magdalena Valley was followed by Late Triassic to Early Jurassic rifting, allowing a sea to cover
Figure 1. View of Nevado del Ruiz volcano and plume, looking toward the southwest. A satellite vent, La Piraña, is visible near the middle left margin.
Figure 2. Nevado del Ruiz as viewed from the city of Manizales, looking toward the southeast. An historically inactive crater, La Olleta, is visible to the right and slightly below the flat summit region, where the active Arenas crater is located.
Figure 3. Generalized location map of Nevado del Ruiz and vicinity, and Colombia (inset).
most of the Northern Andean region. A second subduction zone developed at this time along what is now the Rio Cauca Valley. The westward migration of this second subduction zone to its present location during the Late Cretaceous and Cenozoic produced an accretion of oceanic crust onto the continental margin. Thus, the Romeral Fault which follows the Cauca River Valley to the west of Nevado del Ruiz is thought to be the western limit of continental crust in northern South America. Active volcanism in the Northern Volcanic Zone (NVZ) of the Andean chain (ca. 5°N-2°S) overlies a Benioff zone at approximately 140 km depth and 40-50 km of continental crust (Thorpe, 1984).

The present volcano is built upon the upper Pliocene to lower Quaternary volcaniclastic debris and lava flows of an earlier, "ancestral" Ruiz, and is formed within the probable collapse caldera of this earliest volcanic center (Jaramillo, 1980; Williams and Meyer, 1988; Thouret et al., 1990). Thouret et al. (1990) have recognized three separate eruptive periods over the last 1.8 m.y. at Nevado del Ruiz ("ancestral" Ruiz, "older" Ruiz, and Ruiz), each comprised of a relatively long constructive phase of lava flows and/or dome emplacement, followed by a shorter, often explosive destructive phase resulting in caldera collapse or flank failure. The present summit of Ruiz is a broad, flat area composed of a series of domes which obscure the summit caldera of the "older" Ruiz. These domes were emplaced beginning approximately 0.1 m.y.b.p., and lasting until about 11,000 years ago, when the current "destructive" phase of the volcano was initiated. Williams and Meyer (1988) have proposed a location for the outer caldera boundary fault of the "ancestral" Ruiz complex which delineates a series of outlying vents and domes, the largest of which is La Olleta, a parasitic cone located on the western flank of the volcano, approximately 500 m below the active Arenas summit crater (Figure 4).

Nevado del Ruiz has a well-developed hydrothermal system, with numerous steam vents and hot springs which often emanate at lower elevations along the contact between the metamorphic basement and the overlying volcanic pile. The acid-sulfate-chloride
Figure 4. Proposed caldera boundary fault system for Nevado del Ruiz (from Williams and Meyer, 1988). The enclosed area around the Arenas crater (solid star) is the approximate area covered by glaciers (above ~4800m). Outlying volcanic vents of different types (domes, cinder cones) are indicated with an asterisk and named. El Refugio was a tourist hotel destroyed by the 1985 eruption. Botero Londoño, La Azufrera, and Aguas Calientes are prominent hydrothermal springs or vents.
waters which provide the hot sulfur baths at Hotel Termales (3500 m) are typical of high elevation hot springs on the north and northeast slopes of Ruiz, while a separate alkali-chloride system dominates the lower elevations to the west (Sturchio et al., 1988). The geothermal energy potential of Ruiz-Tolima massif was investigated beginning in the late 1960's, in studies conducted by Central Hidroelectric de Caldas (CHEC), later reported on by Arango et al., (1970) and published in detail by CHEC (1983). The Ruiz geothermal system is believed to be the result of a large thermal anomaly associated with the intrusion of magma at relatively shallow depth below the present summit. Sano et al. (1990) have documented the presence of subduction-type mantle helium and its diffusion through the Ruiz hydrothermal system from the Arenas crater to outlying springs/vents.

RECENT ACTIVITY

Attention began to be focused on Nevado del Ruiz in November of 1984 when seismic and fumarolic activity suddenly increased and persisted into 1985. An explosion from the Arenas crater on September 11, 1985, which was interpreted at the time to be phreatic, cast meter-sized lithic blocks up to a kilometer from the crater and covered the city of Manizales (population 350,000), at a distance of 30 km from the volcano, with a fine layer of ash. This "phreatic" explosion was later found to have released $9 \pm 3 \times 10^4$ metric tons of sulfur dioxide, based on TOMS satellite measurements of plume concentrations (Krueger et al., 1990), a clear indication of magmatic involvement.

At 21:08 on November 13, 1985, after an afternoon of small explosions and intense harmonic tremor, a strong earthquake occurred within the volcano, signalling the start of the eruption of a small volume of pyroclastic material which produced a plinian tephra deposit and generated small pyroclastic flows and surges which ponded atop the flat, glaciated summit and became welded in some areas (Carey et al., 1986; Naranjo et al., 1986; Thouret, 1987; Williams, 1987; Calvache, 1990b; Voight, 1990). Melting of
glacial ice triggered lahars which swept down the steep river canyons on the flanks of the volcano. The deadliest lahars flowed down the Azufrado and Lagunillas River canyons, combined at their juncture, and swept over the town of Armero shortly before midnight, where approximately 23,000 people perished (Lowe et al., 1986; Pierson et al., 1990). Volcanic hazard maps completed only days before the November 13 eruption by INGEOMINAS, Colombia's national bureau of geology and mines, were all too accurate in their assessment of Armero as an area at high risk. The hazard maps revealed that Armero had been built upon the mudflow deposits of two prior historic eruptions in 1595 and 1845, the accounts of which bear striking similarity to the 1985 disaster (Voight, 1990).

The years following the 1985 eruption have been characterized by increasing levels of seismicity and an unusually high, sustained, non-eruptive emission of sulfur dioxide punctuated frequently by small eruptions of non-juvenile lithic ash (Williams et al. 1990). A network of telemetered and smoked-drum seismograph stations monitored by the staff of the Observatorio Vulcanológico de Colombia (OVC) in Manizales has detected seismic swarms not only beneath the Arenas Crater, but also beneath the outlying volcanic domes and vents which delineate the proposed caldera fault boundary. A much smaller eruption than the 1985 event, which took place on September 1, 1989, produced the first fresh magmatic material since 1985, and generated a small lahar which flowed 7 km down the Azufrado River valley.

The slopes of Nevado del Ruiz are mantled by clear, laterally-traceable tephra layers from Ruiz and Cerro Bravo volcano, each layer composed of a basal pumice fall deposit overlain by paleosoils developed during periods of volcanic quiescence. These deposits were noted during investigations of the glacial geology of the area (Herd, 1982) and the last eight Ruiz tephra layers were designated R8 through R1, with R8 being the oldest of the sequence (Figure 5). An earlier deposit, dated at approximately 8600 b.p. is present in the stratigraphy, but is seldom exposed because of its greater depth of burial, and is
Figure 5. Photograph of the airfall tephra layers which mantle the slopes of Nevado del Ruiz volcano approximately 5 km northwest of the Arenas crater. Scaled divisions on ruler are 10 cm in length. R = Ruiz; CB = Cerro Bravo
not included in this study. The eruption of 1985 became R0, now designated R0(a) in this study, as the eruption of 1989 became R0(b). These last two deposits are given the same numeric designation (R0) because, if preserved, they would be temporally indistinguishable from each other in the geologic record, even though they were erupted nearly four years apart. However, due to the small volume and limited coverage of these last two deposits, only a narrow corridor of the 1985 deposit is likely to be preserved, as it is rapidly eroding from the slopes of the volcano away from the main dispersal axis.

At least two other deposits (R2, R7), seem to have been produced by at least two distinct pulses of activity. Due to the small volumes of all the Ruiz deposits, the pulses are subtle and hard to quantify individually, but may suggest that some of the earlier tephra layers, like R0, are actually composite deposits from activity that may have persisted for months or years after the onset of an eruptive phase.

SCOPE AND PURPOSE OF THE STUDY

The tephra deposits at Nevado del Ruiz present a unique opportunity to apply some of the recently developed theoretical models and analytical methods that volcanologists can now use to quantify and reconstruct such important eruption parameters as column height and magma volatile concentration to a complete stratigraphic sequence from a single volcano through time, providing a context in which to view the disastrous eruption of 1985, and the continuing activity of this Northern Andean volcano.

This thesis is part of an integrated study of the overall geology and eruptive history of Nevado del Ruiz volcano being carried out by Dr. Stanley N. Williams and his students at Louisiana State University, and is divided into two main parts. Part I is an investigation into the mineralogy, petrology and volatile content of the pumice deposits associated with eruptions R8-R0. Petrographic data, whole rock analyses, and microprobe analyses of phenocrysts and matrix glasses are used to characterize the sequence through time and to estimate water contents and temperatures of the magmas. This information is used to
compare and contrast earlier eruptions with the well-studied eruption of 1985, and place constraints on the magma source and reservoir system for Ruiz. In addition, this information will serve to increase the data base for Northern Andean volcanism, in general, and specifically for Colombian volcanoes, which represent some of the most active, yet least studied volcanoes in the world.

Part two is an investigation of the physical dynamics of the eruptions which have produced the Ruiz tephra layers. Eruption parameters such as column heights, eruption rates, and volumes are estimated from field measurements using theoretical models of tephra dispersal. Finally, information on previous eruptions is used to reevaluate the volcanic hazard potential at Ruiz, in light of the disastrous results of the eruption of 1985.
PART ONE: PETROGRAPHY AND PETROLOGY
SAMPLES AND ANALYTICAL METHODS

Pumice lumps from each Ruiz airfall layer were sampled at various locations around the volcano and selected for whole rock chemical analysis and petrographic analysis. Eruption R6 is interpreted in Part II of this study to be phreato-magmatic in nature, and is a fine-grained, lithic-rich ash bed, generally without a basal pumice layer. Those rare pumices which are found at the base of R6 are always small (<3 cm), and texturally unique, unlike the typical Ruiz and Cerro Bravo pyroclastics. Isopach and lithic isopleth maps presented in Part II of this study indicate that R6 may have originated from the large adventive cone, La Olleta. Samples of these R6 pumices were collected from two sites on the NW flank of the volcano for analysis and comparison with other Ruiz and Cerro Bravo pumices. Because of the anomalous nature of the R6 deposit, the remaining layers R8 - R0 will be referred to throughout the following text as the "main" Ruiz pumice sequence when it is necessary to denote the exclusion of R6.

Simultaneous fieldwork on the most recent airfall deposits of Nevado del Ruiz and Cerro Bravo volcanoes established that R3 was previously incorrectly interpreted as being a Ruiz deposit. The tephra layer designated as R3 at the localities described in the literature is a Cerro Bravo deposit (CB2), so that Ruiz eruption R3 probably does not exist, and is not included in this study. Correlation of more recent, separately published radiocarbon dates by Lescinsky (1990), has led to a revised chrono-stratigraphic column for the Ruiz-Cerro Bravo sequence, which preserves the original tephra layer designations, but which no longer includes an eruption R3 (Figure 6).

The eruption of 1985, and to a lesser extent, the eruption of 1989 produced a range of megascopically distinct pumices and banded pumices (Figure 7). In general, three major types of pumice comprise the bulk of the ejecta for these two eruptions: 1.) volumetrically-dominant light gray-brown pumice (approximately 85% by volume) 2.) less-abundant white, biotite-rich pumice (10%) 3.) minor dark gray pumice (<5%). Only one obviously
Figure 6. Idealized stratigraphy of the most recent pumice airfall deposits found at Nevado del Ruiz (after Lescinsky, 1990). Section is not drawn to scale. R = Ruiz; CB = Cerro Bravo. Radiocarbon dates: C = CHEC, 1983; H = Herd, 1982; L = Lescinsky, 1990; T = Thouret et al., 1985.
Figure 7. Pumice types erupted in 1985. (a.) (top to bottom) light gray-brown pumice, dark gray pumice, white pumice. (b.) banded pumices.
Figure 7. (cont.)
banded pumice was found within the pre-1985 deposits after hand examination of hundreds of pumice lumps from each eruption layer. Unlike the 1985 tephra, the buried pumices all are approximately the same light brown color from layer to layer and appear essentially homogeneous at the outcrop scale, probably as a result of their compaction, limited exposure, and small volumes. One sample of each of the three types of pumice from eruptions R0(a) and Ro(b) along with pumice samples from eruptions R8-R1 (including R6) from two different locations around the volcano were selected for whole rock analysis. Those samples selected were deemed to be megascopically homogeneous and without secondary alteration to avoid ambiguities. Major and trace element whole rock concentrations were determined with a Siemens SRS 200 X-ray fluorescence spectrometer using Cr and Mo anode X-ray sources at Tulane University in New Orleans, Louisiana after grinding in an alumina shatterbox. Additionally, thin sections of between ten and fifteen pumice lumps were prepared for petrographic and electron microprobe analysis. Individual phenocrysts and pumice matrix glasses were analyzed at LSU in Baton Rouge with a Jeol JSM-T300 scanning electron microscope using energy dispersive spectrometers and a JEOL 733 Superprobe using wavelength dispersive spectrometers. All microprobe analyses of phenocrysts were performed with a 15 kV accelerating voltage, 15.0 nA beam current, and a 1 μm focused spot size. The data were reduced utilizing the Bence-Albee correction procedure (Bence and Albee, 1968). Olivine and pyroxene analyses were calibrated using a combination of well-known standards, Fe-Ti oxides were calibrated against Smithsonian ilmenite and magnetite standards. For matrix glass analyses, sodium losses were minimized by analyzing the samples for sodium first with a count duration of 15 seconds at 15 kV accelerating voltage, 5.0 nA beam current, and a 5 micron spot size. Sodium losses in glass analyses have been corrected by means of the "corundum test"; that is, sodium was added to each analysis until normative corundum was calculated to be between 0 and 0.1 percent. The accuracy of this correction method and the precision of the microprobe analytical procedures used
in all glass analyses was assured by repeated analysis of a separate rhyolite glass standard (Appendix 1). FeO* denotes total iron as FeO, and for all calculations, FeO/FeO* was taken as 0.85. Major element concentrations of whole rock analyses have been recalculated to volatile-free oxide sums of 100% for all diagrams, calculations and classification schemes, while trace element concentrations are unadjusted. The amount of matrix glass (percent melt) for pumices has been calculated by the method of Melson (1983), which assumes that K2O behaves primarily as an incompatible element during crystallization, so that crystallinity is proportional to the amount of K2O in the glass, and the percent glass can be computed by the ratio K_{bu}/K_{mg}, where K_{bu} is the bulk rock concentration of K and K_{mg} is the concentration in the matrix glass. The amounts and abundances of potassic phases such as biotite and hornblende in the Ruiz pumices are too small, except where noted, to affect the matrix glass calculations significantly. Magnetite and ilmenite stoichiometry were calculated from microprobe analyses using the computer program GPP-MINCOMP (Geist et al., 1989). Temperature and oxygen fugacities were calculated using the GPP-TEMP program (Geist et al., 1989), which follows the method of Spencer and Lindsley (1981), as modified by Anderson (1985).

**PETROGRAPHIC OVERVIEW**

In hand specimen, most of the Ruiz pumices are highly phric and virtually indistinguishable from layer to layer. All contain abundant megaporphyritic crystals of tabular, white plagioclase and dark, slender prismatic pyroxene suspended in a hypocrystalline matrix of thick, unevenly vesiculated gray-brown glass. The anomalous pumices associated with eruption R6 are always small (<3 cm) and are less-dense, with smaller crystals in a fine, evenly vesiculated, delicate matrix that probably contributed to its poor preservation at the base of this deposit. Porphyritic biotite is rarely found in hand specimen, except in the white pumices of R0, where millimeter-sized flakes are common. Some white pumices are very dense and crystal-rich, while others are highly
vesiculated and of low density. Banded pumices from the 1985 eruption are usually comprised of patches or streaks of white pumice within darker tephra, but a wide range of other combinations also occur. Previously published estimates of crystal contents for the 1985 pumices range from about 25 to 65 percent by volume (Melson et al., 1990; Vatin-Perignon et al., 1990).

Microscopically, the most abundant crystal phase throughout the entire Ruiz pumice sequence is plagioclase, ranging in size from individual microlites tens of μm long to 5 mm porphyritic laths (Figure 8). Most plagioclase is euhedral, but some crystals show resorbed margins, others have complex internal zonation or contain melt inclusions of brown glass. These melt inclusions may be isolated, occur in bands, or be pervasive enough to impart a sponge or sieve-like texture to the entire phenocryst (Figure 9). A few phenocrysts are resorbed and may contain vesiculated matrix glass within the voids. These "fritted" or spongy phenocrysts are usually some of the largest phenocrysts found within any given thin section; smaller phenocrysts of plagioclase (<1mm) or microlites are not observed to exhibit such textures. The sieve-textured plagioclase phenocrysts occur in pumices from each eruption layer of the main Ruiz sequence, and are most numerous in the darker tephras of the 1985 deposit, least numerous in pumices of eruptions R7 and R8, and were never observed in the white pumices of the 1985 eruption. The pumices of eruption R6 were found not to contain sieve-textured or skeletal plagioclase, but rather, crystals which contain "dusty" inclusion zones typically .05-.1 mm wide and situated near the crystal rim (Figure 10). The R6 plagioclase crystals with dusty zones nearly always appear to be complexly zoned.

Most pumices contain abundant but variable amounts of plagioclase microlites. However, the white pumices of 1985/89 are distinctively different from the bulk of the other Ruiz pumices, in this respect. These pumices have matrix glasses which are free of any microporphyritic quench crystals, including plagioclase, producing well-formed bubble walls that may vary from thick, perfectly formed 100 micron wide "Y"-shaped
Figure 8. Typical Ruiz pumice in thin section. (a.) plane-polarized light. (b.) crossed polars. Sieve-textured plagioclase with dark melt inclusions is visible within the large vesicle, right center. Abundant microlites are visible under crossed polars.
Figure 9. Typical sieve-textured plagioclase in which matrix glass is partially vesiculated. (a.) plane-polarized light (R1). (b.) crossed polars.
Figure 10. Photomicrograph of typical R6 pumice showing dusty zones of melt inclusions within plagioclase and abundant hornblende phenocrysts.
bubble junctions to thin filaments of glass tens of microns wide at the free margins or ends of the vesicle where gas has escaped from within (Figure 11). The vesicle size for the white pumices also is generally larger than typically found in other Ruiz pumice lumps of the same size. Based on image analysis data, Sigurdsson et al. (1990), have shown that for the white pumices of 1985, 4% of the total crystal population is smaller than 200 microns, compared to 20% for other pumices of the same eruption. This lack of microlites in the white pumices is interpreted as having allowed bubble growth to attain larger gas volumes (vesicle size) than glasses impeded by the viscous flow of a glass-microlite mixture. The remainder of the Ruiz pumices have highly variable vesicle sizes and shapes, depending on the crystal content and size of the original lump, but matrix glasses generally become thicker and more opaque with increasing microlite content. In thin section, vesicles are often seen to radiate in all directions from the surfaces of crystals. Having gained a slight advantage over the confining pressure by nucleating on a solid surface, the bubbles grow until sufficient gas pressure within allows them to stream away and separate from the crystal, giving the impression that these crystals were effervescing gases into the magma much like a seltzer tablet in water.

Orthopyroxene and clinopyroxene follow plagioclase in order of abundance, occurring as individual crystals and in glomerophyric clots with other mineral phases. Orthopyroxene prismatic sections may reach 2.0 mm in length, while equant basal sections typically are less than 0.5 mm across. Orthopyroxene is often present as microphenocrysts within the groundmass and may develop as sharp rims surrounding clinopyroxene or olivine cores. Clinopyroxene crystals are weakly pleochroic in light greens and may reach 3 mm in length, and may also occur as a sharp rim around an orthopyroxene core. Both pyroxene phases may contain inclusions of plagioclase, Fe-Ti oxides, apatite, or the other pyroxene. Thin sections of relatively crystal-poor pumices and pumices of eruptions R7 and R8 contain very little clinopyroxene, while crystal-rich pumices and the white pumices of R0 contain greater amounts of clinopyroxene than
Figure 11. Photomicrograph of white pumice from the 1985 eruption showing large, well-formed bubble walls of colorless glass. (a.) plane-polarized light. (b.) crossed polars reveal few microlites.
orthopyroxene. Orthopyroxene crystals generally appear to be optically homogeneous, while clinopyroxene phenocrysts often exhibit complex internal zoning similar to plagioclase. Total crystal content and the relative abundances of plagioclase, orthopyroxene and clinopyroxene vary slightly both within pumices of the same eruption and for the time sequence of deposits, so that no obvious major temporal trends in the modal abundances of these minerals was found, except where noted above. Sigurdsson et al. (1990), have documented a systematic increase in the relative plagioclase content and decrease in pyroxene content from the dark brown to the white pumices of 1985, with the intermediate gray pumices being the most crystal-rich, followed by the white, then the brown pumices.

Minor mineral phases include strongly pleochroic dark-green to golden-brown hornblende and Fe-Ti oxides which occur in roughly equal amounts in the Ruiz sequence. Pumices from each eruption layer (excluding R6, see below) can be placed into one of two categories with respect to hornblende: (1.) those with stable, euhedral hornblende phenocrysts (though always less than 10%) that appear to have been in equilibrium with the melt and (2.) those totally lacking hornblende or containing isolated, corroded crystals with opaque reaction rims that were clearly out of equilibrium with the surrounding melt. Pumices of both types are found within each deposit (excluding R6) suggesting a periodic tapping of a magma chamber zoned with respect to some factor affecting hornblende stability such as water content or pressure. Unlike the other deposits, hornblende is a more abundant crystal phase than pyroxene in the R6 pumices, as up to 2mm elongate and euhedral phenocrysts, with no reaction rims. Iron-titanium oxide minerals are ubiquitous throughout the Ruiz sequence, but are most abundant and largest within the white pumices of R0. Here they occur as individual subequant crystals to 0.4 mm or as larger groups of crystals, and are often found as inclusions in larger phenocryst phases and glomerocrysts. The ulvospinel-magnetite and ilmenite-hematite solid solution pairs are indistinguishable morphologically and appear optically
homogeneous, but backscatter electron imaging reveals slight zoning in some crystals, and abrupt rims around others. Obvious exsolution lamellae textures were found in only 1 of approximately 100 crystals examined with the scanning electron microscope.

Anhedral olivine phenocrysts up to 0.7 mm with spinel inclusions and orthopyroxene reaction rims are common (<1 volume percent) in pumices from eruption R1 and the darkbrown and gray pumices of R0 (Figure 12), but occur much less frequently in pumices from eruptions R2-R6, and no olivine was noted in thin sections of R7, R8, or the white pumices of R0. Clearly out of equilibrium with the melt within which they are found, these crystals are usually less than 1 mm in longest dimension, and are sometimes found within glomerocrystic clots of pyroxene, plagioclase, Fe-Ti oxides and hornblende. Other minor mineral phases include apatite, commonly occurring as inclusions within pyroxene or plagioclase phenocrysts throughout the sequence, and biotite, pleochroic in golden browns, which is found almost exclusively within the white pumices of R0. Biotite may develop as laths up to 5 mm in length, sometimes having been bent or crumpled on eruption. Visual estimation of modal percentage of biotite in the white pumices varies between 1 and 5 percent by volume. Biotite was noted only rarely in thin sections of other pumices throughout the sequence, and was always surrounded by a reaction rim of dark oxides in these instances.

MINERAL CHEMISTRY

The mineralogy of the 1985 airfall and pyroclastic deposits have been previously studied and described in some detail (Gorgaud and Thouret, 1990; Melson et al., 1990; Sigurdsson et al., 1990; Vatin-Perignon et al., 1990). During the early stages of work on this project, it became apparent that the diversity of the magmatic products erupted in 1985 effectively spanned, in one eruption, the entire range of compositions and mineral assemblages of the pre-1985 pumices in the main Ruiz sequence. This conclusion was initially based upon petrographic comparisons, but was later confirmed by the whole
Figure 12. Resorbed olivine xenocryst with orthopyroxene and plagioclase reaction rim (R0). (a.) plane-polarized light. (b.) crossed polars.
rock data which is discussed below. The mineralogical descriptions which follow are in large part a review of the separately published data sets for the 1985 products mentioned above, supplemented with new additional information about the the mineralogy of some of the earlier tephras.

**PLAGIOCLASE**

Some of the investigations into the 1985 pumice mineralogy have focused upon the compositions of the sieve-textured plagioclase phenocrysts and their associated melt inclusions. Plagioclase compositions for the lighter-colored tephras of 1985 range from about An60 at the cores to about An30 at the rims, with reverse zoning rare. The spongy/sieve-textured and resorbed plagioclase phenocrysts of the darker tephras are consistently rather sodic (about An35) and sometimes reversely zoned. Plagioclase in the darker tephras has a wider reported range of composition from about An35 to about An65, while microlite compositions have a more restricted range of An50 to An60. Melt inclusions trapped within phenocrysts may span the compositional range of matrix glass compositions erupted in 1985 (Sigurdsson et al., 1990), but are commonly more evolved compositionally than the matrix glass surrounding the crystal (Melson et al., 1990).

Whole rock compositions for pumices sampled from layers R8-R1 will be shown later in this text to fall between those of the dark and light tephra of R0. Since the petrography of the main Ruiz airfall pumices changes little over the entire sequence, it seems reasonable to assume that the mineralogy of the 1985 pumices probably adequately describes most of what is observed in the earlier tephra. To test this assumption, plagioclase compositions for four eruptions (R8, R7, R6, and R4) were estimated using the method of Michel-Levy. Extinction angles were measured for between fifteen and twenty-five grains in three thin sections of pumices from each of these eruptions, and the results are in good agreement with the reported plagioclase compositions of R0. For eruptions R8 and R7, compositions are estimated to be
between An26 and An63, with a bimodal distribution of compositions near the upper and lower limits of the range. Plagioclase composition estimates for R4 crystals were evenly distributed from An28 to An55, while R6 plagioclase had a restricted range similar to the relatively sodic skeletal or sieve-textured grains found in other Ruiz pumices, with estimated compositions between An26 to An40.

ORTHOPYROXENE

Gorgaud and Thouret (1990) report that orthopyroxene (Opx) in the light-colored tephras of 1985 fall into two narrow groups: (En68-70) and (En74-75). The darker pumices also are reported to fall into two groups, one normally-zoned, with Fe-rich rims of En, and another group of reverse-zoned crystals with Mg-rich rims with sharp bronzite overgrowths. A brief microprobe survey of between seven and twelve pyroxene phenocryst cores and rims within a single thin section from each of the eruptions R1-R8 found only a slightly larger but complete range of compositions than previously reported for R0, falling between about En80 and En64, with crystals from R6 pumice accounting for all analyses between En64 and En65 (Figure 13). Coexisting pyroxene rim compositions typically show about a five percent variation in the En component within the same thin section (Figure 14), except R6 where all five Opx crystals analyzed were found to be between En63 and En65. Figure 14 shows the distribution of coexisting pyroxene core and rim compositions found within a single thin section of pumice from eruption R2. While the overall variation for this sample is greater than was found in some of the other thin sections surveyed, it demonstrates some of the zoning relations typical of all the samples and their similarity to what has been reported for the 1985 pumice. Orthopyroxene cores seem to form two populations at En75-78 and En66-68, while rims of both normal (more Fe-rich rims) and reverse-zoned crystals seem to converge on En70-73. The most Mg-rich compositions (analysis 2aS1-8, Table 1) are sometimes preserved as a reverse-zoned core to middle region, surrounded by a normal-zoned
Figure 13. Range of pyroxene compositions found by microprobe survey of a single thin section from each of the pre-1985 pumice deposits of Nevado del Ruiz (R1-R8).
Figure 14. Relationships between some coexisting pyroxene core and rim compositions found within a single lump of pumice from eruption R2.
<table>
<thead>
<tr>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>FeO*</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>Cr2O3</th>
<th>NiO</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.8</td>
<td>1.51</td>
<td>3.06</td>
<td>6.71</td>
<td>0.41</td>
<td>14.74</td>
<td>21.10</td>
<td>0.49</td>
<td>0.68</td>
<td></td>
<td></td>
<td>100.49</td>
</tr>
<tr>
<td>52.3</td>
<td>0.40</td>
<td>2.29</td>
<td>5.12</td>
<td>0.18</td>
<td>17.91</td>
<td>21.13</td>
<td>0.35</td>
<td>0.01</td>
<td>0.26</td>
<td></td>
<td>99.97</td>
</tr>
<tr>
<td>52.2</td>
<td>0.17</td>
<td>1.13</td>
<td>8.43</td>
<td>0.28</td>
<td>15.13</td>
<td>22.54</td>
<td>0.40</td>
<td>0.01</td>
<td>0.04</td>
<td></td>
<td>100.30</td>
</tr>
<tr>
<td>54.7</td>
<td>0.20</td>
<td>2.68</td>
<td>11.8</td>
<td>0.2</td>
<td>29.20</td>
<td>1.11</td>
<td>0.04</td>
<td></td>
<td>0.15</td>
<td></td>
<td>100.01</td>
</tr>
<tr>
<td>54.2</td>
<td>0.13</td>
<td>0.59</td>
<td>18.3</td>
<td>0.54</td>
<td>24.89</td>
<td>0.97</td>
<td>0.03</td>
<td></td>
<td>0.02</td>
<td></td>
<td>99.67</td>
</tr>
<tr>
<td>52.5</td>
<td>0.95</td>
<td>21.7</td>
<td>0.98</td>
<td>23.48</td>
<td>0.71</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td>100.30</td>
</tr>
<tr>
<td>40.1</td>
<td>0.01</td>
<td>0.01</td>
<td>13.4</td>
<td>0.24</td>
<td>46.54</td>
<td>0.13</td>
<td></td>
<td></td>
<td>0.24</td>
<td></td>
<td>100.66</td>
</tr>
<tr>
<td>39.5</td>
<td>0.03</td>
<td>16.0</td>
<td>0.22</td>
<td>43.94</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td>0.28</td>
<td></td>
<td>100.13</td>
</tr>
<tr>
<td>40.8</td>
<td>0.03</td>
<td>10.1</td>
<td>0.17</td>
<td>49.08</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td>0.29</td>
<td></td>
<td>100.58</td>
</tr>
</tbody>
</table>

Table 1. Representative microprobe analyses of olivine and pyroxene phenocrysts found within the pre-1985 pumice deposits of Nevado del Ruiz (R1-R8).
middle to outer rim (Figure 15). The reverse zoned crystals usually contain cores which fall into the higher Fe group at En66-68. Selected orthopyroxene analyses which describe the range of variation observed are reported in Table 1.

**CLINOPYROXENE**

Vatin-Perignon et al. (1990) report two populations of clinopyroxene (Cpx) within the 1985 tephra, one group more Mg-rich (average composition Wo40 En48 Fs12) than the other, and similar to compositions found in glomerocrystic clusters. Sigurdsson et al. (1990) note that these high-Mg clinopyroxenes and the glomerocrysts of plagioclase, pyroxene, and Fe-Ti oxides may be xenocrystic and share a common source with the embayed olivine crystals. Gorgaud and Thouret (1990) report a narrow compositional range for Cpx phenocrysts in 1985 pumice (Wo39-44 En42-48 Fs10-16), with strong reverse-zoning (rims richer in Mg) in some phenocrysts within the darker tephras. Our survey of the older tephras produced a very similar range of values for Cpx (Wo42-46 En40-49 Fs8-16) (Figure 13). Cr$_2$O$_3$ contents in augite phenocrysts are as high as 0.79 weight percent, but only about twenty percent of all the crystals analyzed have Cr$_2$O$_3$ contents greater than 0.10 percent. Melson et al. (1990) report Cr$_2$O$_3$ contents as high as 0.94 weight percent in the 1985 pumice. No pigeonite was found within the pre-1985 pumices, but scarce phenocrysts have been reported to occur in R0 tephra (Sigurdsson et al., 1990). Compositional variations among coexisting Cpx crystals in pre-1985 tephras are similar to that observed in Opx and Cpx of 1985, with normal and reverse zoning, and normal zoning surrounding a reverse-zoned core to middle region (Figure 15). No distinctly separate core populations were observed, with variations covering most of the indicated range of Cpx compositions. Select clinopyroxene analyses are reported in Table 1.
Figure 15. Zoning patterns in four coexisting pyroxene phenocrysts within a single lump of pumice from eruption R2. Separate crystals are enclosed by dashed lines.
OLIVINE

Gorgaud and Thouret (1990) have reported normal zoning and a range of $F_{084.87}$ for the cores of embayed olivine phenocrysts in R0 pumice and $F_{079.84}$ for their rims. Vatin-Perignon et al. (1990) report a similar range of $F_{086.79}$. Melson et al. (1990) report a range of $F_{074.88}$, with Ni contents between 1700 and 2800 ppm. Melson et al. also argue that magmas of a composition such as the darker pumices of eruption R0 would have a small amount of olivine on a calculated 1-atm anhydrous liquidus, but that it is soon replaced by hypersthene with decreasing temperature, and thus, the resorbed and Opx-mantled olivine could be a primary phase. Melson et al. also find that the Ni contents of these olivines are only slightly higher than predicted based on extrapolations of Ni partitioning between olivine and the melt, but also point out that the crystals which contain high-Cr spinels are unlikely to have crystallized from the Ruiz magma. Gorgaud and Thouret (1990) find that Ruiz olivines show a strong departure from the predicted equilibrium value of Mg-Fe partitioning between olivine and Opx. Our brief survey of approximately fifteen hypersthene-mantled olivine phenocrysts in thin sections of pumice from eruptions R2 and R6 found the R2 olivines normally and reverse-zoned, all with core compositions of about $F_{086}$ and rim compositions at about $F_{083}$. Some middle regions between core and rim were reverse zoned to $F_{088}$. Olivines in R6 pumice were found to be normally zoned, with cores slightly more Mg-rich than other Ruiz pumices at $F_{090}$ and rims at $F_{088}$. NiO contents range from 0.22 to 0.32 weight percent for R2 and R6 olivines, and were usually found to be the highest just inside the rim of the crystal. Data on the compositions of synthetic coexisting olivine and Opx indicates that olivine is slightly iron-rich in comparison to coexisting Opx between 900 and 1000°C (Matsui and Nishizawa, 1974). Our microprobe analyses show the reverse to be true and support the assertion of Gorgaud and Thouret (1990) that the olivines found in the Ruiz pumices are too Mg-rich to have coexisted with the Opx with which they are found. Our data indicates $0.73 < \frac{Mg}{Mg+Fe} < 0.83$ for olivines, and
0.52 < Mg/Mg+Fe < 0.71 for Opx. Based on the above arguments, and because olivine occurs only sporadically throughout the Ruiz sequence, we consider these crystals of olivine to be xenocrysts, originating in a more basic magma component of the Ruiz reservoir system. Representative olivine analyses are reported in Table 1.

Vatin-Perignon et al. (1990) report the composition of amphibole in isolated crystals and in clusters with other minerals as pargasitic (XMg=0.72-0.75), with the Mg-rich phenocrysts often resorbed and rimmed with Fe-Ti oxides. Gorgaud and Thouret (1990) find that the hornblende in the white pumices is edenitic, while only pargasite was present in the black and gray scoria. Microprobe analyses of hornblende in pumice from R2 and R6 find no major compositional differences between these phenocrysts and those reported by Melson et al. (1990). Biotite is consistently reported as having a uniform composition of phlogopite in R0 pumice (Gorgaud and Thouret, 1990; Vatin-Perignon et al., 1990), and we find it to be an extremely rare mineral phase in the pre-1985 deposits.

Microprobe analyses of two coexisting magnetite-ilmenite pairs from one sample each of dark brown, gray and white pumice from the 1985 eruption are listed in Table 2 with temperature and oxygen fugacity determinations. Our results indicate that the white pumice is the most oxidizing of the three, with the lowest indicated temperature range of 853-858°C, with the dark brown and gray-brown pumice slightly hotter and between 916-928°C. Thus, we agree with the assertion of Melson et al. (1990) that the remarkable ability of the small-volume, crystal-rich pyroclastic flows to become welded in some areas must be attributed to the unusually flat summit region of Ruiz and partial remelting of matrix glass by the fluxing action of trapped water and entrained meltwater, rather than supra-liquidus emplacement temperatures.

These main points summarize the petrography and mineralogy of the Ruiz pumice sequence:

1. The samples are often very crystal-rich, with the phenocryst assemblage of the main
Table 2. Microprobe analyses, crystal equilibration temperatures, and oxygen fugacities for two ilmenite-magnetite pairs for each of the three dominant types of pumice erupted in 1985. The uncertainties for the temperature and oxygen fugacity calculations are approximately 40-80°C and 0.5-1.0 log units, respectively, assuming a ±1% uncertainty in analytical precision (Spencer and Lindsley, 1981). RO-W = white pumice; RO-G = gray pumice; ROmml = brown pumice.

<table>
<thead>
<tr>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Cr₂O₃</th>
<th>FeO*</th>
<th>MnO</th>
<th>MgO</th>
<th>Total</th>
<th>T (°C)</th>
<th>Log fO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample RO-W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>36.81</td>
<td>0.23</td>
<td>0.08</td>
<td>55.33</td>
<td>0.39</td>
<td>2.34</td>
<td>95.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>6.53</td>
<td>1.61</td>
<td>0.36</td>
<td>81.50</td>
<td>0.36</td>
<td>1.61</td>
<td>92.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>36.94</td>
<td>0.23</td>
<td>0.09</td>
<td>56.76</td>
<td>0.37</td>
<td>2.37</td>
<td>96.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>6.80</td>
<td>1.61</td>
<td>0.33</td>
<td>83.02</td>
<td>0.35</td>
<td>1.61</td>
<td>93.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample RO-G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>35.76</td>
<td>0.27</td>
<td>0.09</td>
<td>53.12</td>
<td>0.27</td>
<td>2.38</td>
<td>91.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>9.17</td>
<td>1.70</td>
<td>0.41</td>
<td>75.67</td>
<td>0.33</td>
<td>1.99</td>
<td>89.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.03</td>
<td>35.34</td>
<td>0.30</td>
<td>0.09</td>
<td>53.63</td>
<td>0.24</td>
<td>2.39</td>
<td>92.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td>9.88</td>
<td>1.70</td>
<td>0.37</td>
<td>75.56</td>
<td>0.36</td>
<td>2.06</td>
<td>90.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample ROmml</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>30.72</td>
<td>0.78</td>
<td>0.19</td>
<td>57.78</td>
<td>0.10</td>
<td>3.08</td>
<td>92.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>7.43</td>
<td>2.13</td>
<td>0.43</td>
<td>78.01</td>
<td>0.28</td>
<td>2.99</td>
<td>91.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>33.52</td>
<td>0.43</td>
<td>0.47</td>
<td>57.20</td>
<td>0.20</td>
<td>2.65</td>
<td>94.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>8.11</td>
<td>4.00</td>
<td>0.63</td>
<td>74.54</td>
<td>0.27</td>
<td>4.04</td>
<td>91.71</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ruiz sequence characterized by plag + opx + cpx + Fe-Ti oxides. Crystal content and the relative abundances of the major mineral phases vary slightly within each deposit, but no major temporal trends in petrography or mineralogy were observed. The eruption of 1985 produced the widest range of tephra types and textures, but the bulk of the 1985 deposit is very similar to the layers of Ruiz pumice buried beneath it.

2. Some samples of the main Ruiz sequence contain hornblende as a stable minor phase, while it is out of equilibrium in other samples from the same deposit, implying volatile stratification within the pre-eruption magma chamber. Disequilibrium mineral assemblages, overgrowths, complex crystal zoning, and bimodal crystal populations may indicate mixing, perhaps due to convective overturn within the magma chamber producing progressively changing crystallization conditions prior to eruption.

3. Olivine is an important accessory mineral only in the most recent tephra, and is most abundant within the pumices of eruption R1 and the dark brown and gray-brown pumices of R0, but is absent from the white pumices of the same eruption. These crystals are probably remnants of a more basic magmatic component not otherwise represented in the tephra.

4. The volumetrically-minor white pumices of R0 are characterized by an assemblage of larger phenocrysts of plag + cpx + opx + Fe-Ti oxides + biotite. Matrix glasses are distinctively clear and free of microlites, and generally attain larger vesicle size than the other Ruiz pumices. Fe-Ti oxide geothermometry indicates a temperature of 853-858°C, which is about 75° cooler than the co-erupted dark brown and gray-brown pumices. The petrographic characteristics of the R0 white pumice has also been observed in a megascopically homogeneous sample of pumice from eruption R5, juxtaposed against, but not mixed with the normal microlite-rich glass, in a texture similar to the banded pumices of 1985. This suggests that the pre-1985 deposits may also be rather heterogeneous, although this is not obvious in hand sample or at the outcrop scale.

5. The rare pumices associated with layer R6 are petrographically and mineralogically
different from the main sequence of Ruiz pumices, and are characterized by the assemblage plag + hbl + opx + Fe-Ti oxides, implying a separate magma source for this tephra.

6. There is evidence of limited mixing of the distinct magma batches which were erupted in 1985. It is likely that the large resorbed or sieve-textured sodic plagioclase and jacketed biotite phenocrysts within the darker tephras were incorporated from the cooler batch of light-colored magma as a result of convective overturn within the magma chamber. The dark brown and gray tephras of 1985 seem to be hybrid rocks which contain phenocrysts that are out of equilibrium with the melt in which they are found. Some of these phenocrysts (olivines) probably have origins within more basic melts, or possibly spinel peridotites, while others (resorbed plagioclase, biotite) were probably stable within more acidic magmas. By contrast, there seems to be no evidence of incorporation of the hotter, darker batch into the magma which produced the white pumices (i.e. no olivines or microlites in the white pumices), and the white pumices are probably pure samples of what will be shown to be the most differentiated "end member" of the Ruiz magmatic products.

WHOLE ROCK ANALYSES

A total of twenty samples of pumice from the Ruiz pyroclastic sequence were selected for bulk chemical analysis (Table 3). These specimens included three samples each from the most recent eruptions R0(a) and R0(b), and two samples from each of the remaining seven layers (R1-R8), taken from different sites around the volcano. For eruptions R0(a) and R0(b), one megascopically homogeneous specimen, representative of each of the three dominant types of pumice found in those deposits (dark brown, gray, and white) was selected for analysis. Major and trace element concentrations for the samples used in this study are listed in Table 3 and Harker variation diagrams of these results are presented in Figure 16.
Table 3. Whole rock analyses of pumice lumps from the Ruiz pyroclastic sequence as determined by XRF. Major elements are in weight percent, trace elements in parts per million. FeO* is total Fe as FeO. Estimated errors in analyses are shown below as a percentage of the amount present for each element. SiO2 (0.8%), TiO2 (2%), Al2O3 (2%), FeO (0.9%), MnO (5%), MgO (3%), CaO (0.7%), Na2O (3%), K2O (0.8%), P2O5 (3%), Rb (6%), Sr (5%), Y (10%), Zr (4%), Nb (10%), Ba (5%), La (12%), Cu (5%), Ni (10%), Zn (10%), Cr (6%), V (5%).

1. M1 - Gray pumice, 1989 eruption
2. M2 - Dark brown pumice, 1989 eruption
3. M3 - White pumice, 1989 eruption
4. ROW - White pumice, 1985 eruption
5. ROG - Gray pumice, 1985 eruption
6. ROS5 - Dark brown pumice, 1985 eruption
7. All other samples are brown pumices from layers R1-R8 from different sites (S) around the volcano and are designated as such.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>ROW</th>
<th>ROG</th>
<th>ROS5</th>
<th>R1S3</th>
<th>R1S9</th>
<th>R2S2</th>
<th>R2S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>62.50</td>
<td>62.10</td>
<td>65.10</td>
<td>66.23</td>
<td>63.55</td>
<td>62.61</td>
<td>61.76</td>
<td>62.83</td>
<td>63.87</td>
<td>62.81</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.72</td>
<td>0.76</td>
<td>0.61</td>
<td>0.56</td>
<td>0.66</td>
<td>0.73</td>
<td>0.76</td>
<td>0.67</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>FeO*</td>
<td>4.98</td>
<td>5.54</td>
<td>4.43</td>
<td>3.74</td>
<td>4.64</td>
<td>4.91</td>
<td>5.23</td>
<td>4.93</td>
<td>4.39</td>
<td>4.59</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.10</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>MgO</td>
<td>2.50</td>
<td>2.40</td>
<td>2.10</td>
<td>2.26</td>
<td>3.18</td>
<td>4.11</td>
<td>3.51</td>
<td>2.91</td>
<td>2.61</td>
<td>2.78</td>
</tr>
<tr>
<td>CaO</td>
<td>5.77</td>
<td>6.03</td>
<td>4.57</td>
<td>4.27</td>
<td>5.27</td>
<td>5.52</td>
<td>5.40</td>
<td>5.38</td>
<td>4.89</td>
<td>5.16</td>
</tr>
<tr>
<td>Na2O</td>
<td>4.00</td>
<td>3.90</td>
<td>4.00</td>
<td>4.21</td>
<td>4.27</td>
<td>4.09</td>
<td>4.02</td>
<td>4.02</td>
<td>4.23</td>
<td>4.14</td>
</tr>
<tr>
<td>K2O</td>
<td>2.26</td>
<td>2.15</td>
<td>2.75</td>
<td>3.02</td>
<td>2.48</td>
<td>2.29</td>
<td>2.24</td>
<td>2.09</td>
<td>2.57</td>
<td>2.34</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.20</td>
<td>0.20</td>
<td>0.22</td>
<td>0.17</td>
<td>0.20</td>
<td>0.21</td>
<td>0.23</td>
<td>0.21</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Total</td>
<td>99.77</td>
<td>99.48</td>
<td>99.86</td>
<td>100.86</td>
<td>100.96</td>
<td>100.96</td>
<td>99.32</td>
<td>99.38</td>
<td>100.02</td>
<td>99.20</td>
</tr>
</tbody>
</table>

Rb    | 65 | 63 | 83 | 85 | 65 | 61 | 56 | 48 | 60 | 60 |
Sr    | 575 | 552 | 529 | 523 | 542 | 536 | 576 | 566 | 561 | 577 |
Y     | 17 | 18 | 17 | 17 | 16 | 17 | 17 | 17 | 16 | 17 |
Zr    | 156 | 158 | 172 | 168 | 145 | 145 | 141 | 138 | 146 | 149 |
Nb    | 7 | 12 | 9 | 6 | 7 | 9 | 11 | 10 | 11 |
Cu    | 48 | 45 | 26 | 28 | 40 | 44 | 40 | 33 | 41 | 38 |
Ni    | 13 | 12 | 20 | 20 | 45 | 57 | 49 | 34 | 32 | 30 |
Zn    | 73 | 75 | 64 | 55 | 69 | 64 | 69 | 68 | 61 | 67 |
Ba    | 1062 | 1005 | 1209 | 1231 | 1087 | 1036 | 1075 | 1038 | 1161 | 1107 |
Cr    | 55 | 64 | 28 | 70 | 148 | 180 | 139 | 135 | 108 | 83 |
V     | 128 | 147 | 83 | 47 | 75 | 95 | 101 | 85 | 71 | 81 |
La    | 98 | 118 | 82 | 30 | 19 | 17 | 14 | 13 | 24 | 17 |
<table>
<thead>
<tr>
<th></th>
<th>R4S2</th>
<th>R4S6</th>
<th>R5S3</th>
<th>R5S13</th>
<th>R6S9</th>
<th>R6S15</th>
<th>R7S3</th>
<th>R7S14</th>
<th>R8S3</th>
<th>R8S14</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>64.21</td>
<td>64.16</td>
<td>61.32</td>
<td>62.91</td>
<td>64.56</td>
<td>62.85</td>
<td>60.84</td>
<td>61.73</td>
<td>59.35</td>
<td>60.20</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.67</td>
<td>0.65</td>
<td>0.75</td>
<td>0.67</td>
<td>0.57</td>
<td>0.63</td>
<td>0.75</td>
<td>0.76</td>
<td>0.79</td>
<td>0.77</td>
</tr>
<tr>
<td>FeO*</td>
<td>4.37</td>
<td>4.27</td>
<td>5.16</td>
<td>4.41</td>
<td>4.18</td>
<td>4.51</td>
<td>4.71</td>
<td>4.54</td>
<td>5.07</td>
<td>4.85</td>
</tr>
<tr>
<td>MnO</td>
<td>0.08</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>MgO</td>
<td>2.39</td>
<td>2.39</td>
<td>2.78</td>
<td>2.88</td>
<td>2.08</td>
<td>2.60</td>
<td>2.91</td>
<td>2.76</td>
<td>2.74</td>
<td>2.50</td>
</tr>
<tr>
<td>CaO</td>
<td>4.71</td>
<td>4.72</td>
<td>5.49</td>
<td>5.36</td>
<td>4.71</td>
<td>5.21</td>
<td>5.19</td>
<td>5.02</td>
<td>5.48</td>
<td>5.10</td>
</tr>
<tr>
<td>Na2O</td>
<td>4.25</td>
<td>4.08</td>
<td>4.09</td>
<td>4.19</td>
<td>4.00</td>
<td>4.10</td>
<td>3.98</td>
<td>3.95</td>
<td>4.08</td>
<td>4.06</td>
</tr>
<tr>
<td>K2O</td>
<td>2.54</td>
<td>2.48</td>
<td>2.27</td>
<td>2.33</td>
<td>1.87</td>
<td>1.66</td>
<td>2.19</td>
<td>2.33</td>
<td>2.02</td>
<td>2.21</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.19</td>
<td>0.14</td>
<td>0.13</td>
<td>0.23</td>
<td>0.23</td>
<td>0.24</td>
<td>0.22</td>
</tr>
<tr>
<td>Total</td>
<td>99.95</td>
<td>99.36</td>
<td>99.06</td>
<td>99.97</td>
<td>98.28</td>
<td>98.05</td>
<td>97.59</td>
<td>98.14</td>
<td>97.25</td>
<td>96.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Rb</th>
<th>Sr</th>
<th>Y</th>
<th>Zr</th>
<th>Nb</th>
<th>Cu</th>
<th>Ni</th>
<th>Zn</th>
<th>Ba</th>
<th>Cr</th>
<th>V</th>
<th>La</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb</td>
<td>65</td>
<td>65</td>
<td>55</td>
<td>60</td>
<td>41</td>
<td>37</td>
<td>56</td>
<td>57</td>
<td>51</td>
<td>54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>584</td>
<td>579</td>
<td>565</td>
<td>587</td>
<td>602</td>
<td>633</td>
<td>595</td>
<td>609</td>
<td>672</td>
<td>655</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>16</td>
<td>15</td>
<td>14</td>
<td>17</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>151</td>
<td>152</td>
<td>142</td>
<td>145</td>
<td>147</td>
<td>136</td>
<td>155</td>
<td>148</td>
<td>152</td>
<td>154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>33</td>
<td>41</td>
<td>38</td>
<td>33</td>
<td>18</td>
<td>21</td>
<td>45</td>
<td>37</td>
<td>40</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>25</td>
<td>24</td>
<td>23</td>
<td>23</td>
<td>11</td>
<td>19</td>
<td>36</td>
<td>35</td>
<td>20</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>63</td>
<td>67</td>
<td>69</td>
<td>62</td>
<td>66</td>
<td>69</td>
<td>70</td>
<td>61</td>
<td>67</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>1191</td>
<td>1172</td>
<td>1040</td>
<td>1074</td>
<td>1133</td>
<td>1045</td>
<td>1115</td>
<td>1124</td>
<td>1068</td>
<td>1086</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>72</td>
<td>68</td>
<td>51</td>
<td>48</td>
<td>85</td>
<td>84</td>
<td>103</td>
<td>86</td>
<td>48</td>
<td>49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>68</td>
<td>66</td>
<td>95</td>
<td>68</td>
<td>63</td>
<td>74</td>
<td>86</td>
<td>81</td>
<td>96</td>
<td>91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>La</td>
<td>16</td>
<td>20</td>
<td>14</td>
<td>19</td>
<td>10</td>
<td>19</td>
<td>17</td>
<td>17</td>
<td>12</td>
<td>19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. (cont.)
Figure 16. Harker variation diagrams for major and trace element whole rock concentrations as determined by XRF for samples from deposits R8 - R0. Symbols and data are from Table 3.
Figure 16. (cont.)
Based on the classification system of Gill (1981), the Ruiz pumices are transitional between medium- and high-K acid andesites to dacites, with only the most siliceous analyses plotting well within the high-K field (Figure 17). The K2O-SiO2 trend of the pumices of the main Ruiz sequence is offset from a separate trend defined by the R6 analyses that is lower in K2O content. Similar compositional offsets are present in diagrams of Ca, P, Rb, Ba, Cu, Y, and Zr versus SiO2 (Figure 16). In a separate study of the older magmatic products of Ruiz (pyroclastic flows, lavas, dome rocks, etc.), Schaefer and Williams (1989) have identified two separate K2O-SiO2 trends which match the compositional offsets of the tephras. While most rocks in the Schaefer and Williams study follow the same compositional trends of the main Ruiz airfall pumices, a few match the trends of the R6 pumice. Samples which match the lower-K trend of the R6 pumice are dome rocks from two locations:

1. the domes, Alto de Santana and Alto de la Laguna, which lie along the proposed outer caldera boundary fault (Figure 3).
2. a block-and ash-flow deposit below the Arenas crater near Rio Guali, related to the collapse of dome rocks which form the present summit of Ruiz.

Since R6 is thought to have originated from the parasitic crater La Olleta, such compositional offsets between R6 and the main Ruiz sequence imply a dual nature of evolutionary paths or separate magma sources for ejecta erupted from adjacent conduits that may be controlled by a complex caldera fault network. Separate K2O-SiO2 correlations with different slopes have been previously reported at Guntur volcano, Java (Whitford and Nichols, 1976), and at Aoba and Ambrym volcanoes, New Hebrides (Gorton, 1977) where the duality of the K2O-SiO2 slopes may be accompanied by differences in petrography, which is the case for the R6 pumices.

Figure 18 plots silica content versus time for the main Ruiz airfall sequence. By excluding the R6 pumices, there appears to be some definite trends in silica content for the main Ruiz sequence over time. First, there is a general increase in silica content from
Figure 17. Classification of the Ruiz pumices based on whole rock analyses according to the scheme of Gill, 1981. Dashed lines indicate separate potassium-silica trends for the main Ruiz pumices and R6. Symbols are from Table 3.
Figure 18. Plot of whole rock silica content versus time for the main Ruiz sequence (R6 excluded). Dashed lines with arrows indicate general trends in silica over time.
eruptions R8 to R4, followed by a steady decrease in silica and increase in eruption frequency, most recently with the eruption of heterogeneous pumice types spanning a compositional range of more than 2 weight percent silica. Eruption frequency for layers R8 through R4 averages approximately 1 eruption every 500 years, while for eruptions R4 through R0, the frequency is 1 eruption every 180 years if R0(a) and R0(b) are treated as one layer.

The highest silica, highest potassium analyses belong to the white pumices of the 1985/1989 eruptions, while the darker pumices of these same eruptions are similar to or slightly lower in silica than most of the earlier eruptions (Figures 16, 17, 18). Due to the lack of a sufficiently large number of analyses of R0 pumice, it is unclear whether a complete continuum in whole rock silica content exists between the dark brown and gray andesites with less than 63% silica and the white dacites with greater than 65% silica, or if the compositional gap depicted in Figure 18 is real. Sigurdsson et al. (1990) report an apparent compositional gap in matrix glass compositions between andesitic and dacitic pumices, but find no such gap in whole rock or melt inclusion compositions.

Compilations of the reported whole rock compositions for the 1985 Ruiz pumice from 5 separate sources, including this study, are presented in Figure 19. While whole rock data produced by different analytical methods (XRF, microprobe analyses of fused glasses) are not strictly comparable, Figure 19 seems to indicate that for the whole rock data set for R0, there is no compositional gap in silica content between the dark andesites and white dacites. Other incompatible elements K and Rb, as well as their ratio (Figure 20) also fail to show a compositional gap, but like silica, do show a clear bimodal distribution. Such a bimodal distribution may indicate two separate populations or batches of magma originally separate from each other which have undergone limited mixing to produce a less-abundant, but complete range of intermediate products. However, sampling bias must be assumed to be insignificant for this interpretation to be valid. The individual histograms for each of the other four sources used in this
Figure 19. Distribution of reported concentrations of SiO$_2$, K$_2$O and Rb in whole rock analyses of 1985 Ruiz pumice. Graphs for SiO$_2$ and K$_2$O (wt. percent) represent a total of 61 analyses from this study and the following sources: Gorgaud and Thouret, 1990; Melson et al., 1990; Sigurdsson et al., 1990; and Vatin-Perignon et al., 1990. Rb (ppm) data is for 32 analyses presented in this study and the last three of the four references listed above.
Figure 20. Plot of reported K$_2$O versus Rb ratios for whole rock analyses of 1985 Ruiz pumice. Data represents a total of 32 analyses from this study and the following sources: Melson et al., 1990; Sigurdsson et al., 1990; and Vatin-Perignon et al., 1990.
compilation are included in Appendix 2.

MAJOR ELEMENTS

The Harker variation diagrams in Figure 16 demonstrate that for the Ruiz pumices, K2O and TiO2 show the strongest correlation with silica content. For the main Ruiz pumice sequence, K2O and TiO2 have correlation coefficients of 0.795 and 0.786, respectively, while MnO (0.048) and Na2O (0.016) show little relation to silica content. Relative concentrations of FeO* and MgO vary by as much as a factor of two, but lie clearly in the calc-alkaline field in a plot of FeO*/MgO vs. SiO2 (Figure 21). The average Mg-number (Mg/Mg + Fe) X 100 of the Ruiz pumices is approximately 38, compared to approximately 57 for average andesites (Gill, 1981). The highest Mg-number and the largest absolute concentration of MgO in the samples analyzed belongs to the dark brown pumice of the 1985 eruption (analysis R0S5, Table 3), which as a group contain the greatest amount of olivine observed in thin section.

TRACE ELEMENTS

Ba and Rb behave as incompatible elements during fractional crystallization and show the strongest positive correlation with silica (correlation coefficients 0.715 and 0.631), respectively, while La (0.017), Y (0.014), and Nb (0.009) show little systematic variation (Figure 11). Cr concentrations are highly variable (a factor of 3) for pumices with silica contents between 62 and 63 percent. The analyses with Cr levels above 125 ppm belong to the dark pumices of R0 and the pumices of R1, which as mentioned, also show high MgO levels and modal olivine in thin section. Thus, the offset between the relatively low Cr values for R8 and R5 pumice and the higher Cr levels for R0 and R1 reflects an influx of xenocrystic Cr-spinel-bearing olivine into the Ruiz magma reservoir during the most recent eruptions.

Average Ba concentrations for the Ruiz pumices are as much as 53% greater than
Figure 21. Whole rock analyses of Ruiz pumice fall within the calc-alkaline field in a plot of FeO*/MgO versus SiO₂. Symbols are from Table 3.
the average concentrations for the more generally well-studied volcanics of Middle America (Mexico, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica) and Western South America (Andean Ecuador, Chile, and Peru) which are compiled and listed in Ewart (1979). Since the behavior of Ba is known to be closely correlated with K during fractional crystallization, it should be noted that K is not similarly enriched in these rocks and average K\textsubscript{2}O for Ruiz pumices is roughly between the averages for these other suites. Melson et al. (1990) note that Ba/La ratios range from 49 to 62 in Ruiz pyroclastics, while lavas from other andesitic Andean centers typically have Ba/La ratios of 12 to 30. Recent petrological data from other Colombian volcanoes (Volcán Galeras in Calvache, 1990a; and Volcán Cerro Bravo in Lescinsky, 1990) reveals that Ruiz is not unique among Northern Andean volcanoes in having elevated Ba magmas. Such a regional trend in trace element concentration argues for a common, large-scale tectono-orogenic source for Ba enrichment in the Northern Andes, involving the overlying crust or subducted slab. Kay and Kay (1988) have reviewed the process of upper crustal recycling of elements such as Ba which have been selectively concentrated by the hydrosphere-sediment system and subducted as part of the oceanic crust. Their findings indicate that the trace element compositions of Pacific oceanic sediments are variable and mixing during the subduction process is necessary to produce elements in the ratios found in Aleutian arc magmas.

Unlike Ba, Rb which also generally follows K during crystallization, does not show enrichment in the Ruiz magmas. A plot of Rb vs. K/Rb (Figure 22) reveals that the Ruiz whole rock data are essentially transitional between the calc-alkaline (medium-K) series and high-K series, which is in good agreement with their general classification based on SiO\textsubscript{2}/K\textsubscript{2}O ratio (Figure 17).

**MATRIX GLASS CHEMISTRY AND WATER CONTENT ESTIMATES**

_Since H\textsubscript{2}O is the dominant volatile phase in dacitic melts, and H\textsubscript{2}O content is_
Figure 22. Ruiz whole rock analyses in a plot of Rb versus K/Rb. After Ewart, 1979.
perhaps the single most important factor that affects mineral liquidus temperatures, melt viscosity, and explosive behavior, a magmatic geohyugrometer is a useful tool that can be used to place constraints on this important component of the eruptive magma chamber. Water contents of the melts which produced various Ruiz pumices have been estimated by applying the geohyugrometer of Merzbacher and Eggler (1984) which is based on the assumption that for melts of this type, the effect of H2O dominates over other volatiles, and that these melts respond to changes in water content by the melting or crystallization of mineral phases. Accuracy of the geohyugrometer is reported to be approximately ± 1%.

For the eruption of 1985, matrix glasses of the three major types of pumices used for whole rock analyses (dark brown, gray, and white) were also selected for microprobe analysis. Major element concentrations for matrix glass compositions (Table 4) show approximately a ten weight percent difference in SiO2 between the andesitic glass of the dark brown pumices (Sample R0mm-1) and the rhyolitic glass of the white pumice (Sample R0-W). Plotting R0 matrix glass compositions onto the geohyugrometer ternary diagram of Merzbacher and Eggler, 1984 (Figure 23a) reveals a systematic increase in water content from the relatively dryer (and hotter) dark brown pumices with 0-1 % water to the cooler white pumices which plot outside the calibrated field, but are inferred to have water contents of 2-3 %. Whole rock data for the R0 pumice, also plotted in Figure 23a, show the same general relationship in terms of water content as do the matrix glasses, but also demonstrate some of the possible evolutionary trends of the melts involved. Assuming the whole rock compositions to be suitable starting points for the evolution of matrix glasses, a path from the dark brown pumice (Sample R0S5) whole rock composition to its corresponding matrix glass involves a slight dewatering trend which is repeated for the gray pumice (RO-G). This is less apparent for the white pumice which seems to have evolved along the 2% water contour, possibly with a slight increase in water from bulk rock to matrix glass. The actual evolutionary "paths" of these melts may be much more complicated than the generalizations used here, in
<table>
<thead>
<tr>
<th>Sample: R0-W</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>FeO*</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>P2O5</th>
<th>Total</th>
<th>KBu</th>
<th>% Melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>73.48</td>
<td>0.28</td>
<td>12.14</td>
<td>0.96</td>
<td>0.16</td>
<td>0.70</td>
<td>3.31</td>
<td>5.01</td>
<td>0.01</td>
<td>96.05</td>
<td>3.02</td>
<td>60.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.98</td>
<td>0.19</td>
<td>12.33</td>
<td>1.01</td>
<td>0.13</td>
<td>0.70</td>
<td>3.40</td>
<td>5.04</td>
<td>0.04</td>
<td>96.79</td>
<td>3.02</td>
<td>59.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.73</td>
<td>0.18</td>
<td>12.36</td>
<td>0.99</td>
<td>0.15</td>
<td>0.71</td>
<td>3.43</td>
<td>5.00</td>
<td>0.01</td>
<td>96.55</td>
<td>3.02</td>
<td>60.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample: R0-G-1</td>
<td>67.35</td>
<td>0.80</td>
<td>15.68</td>
<td>3.81</td>
<td>0.09</td>
<td>1.12</td>
<td>3.01</td>
<td>4.36</td>
<td>3.27</td>
<td>0.23</td>
<td>99.72</td>
<td>2.48</td>
<td>75.80</td>
</tr>
<tr>
<td>66.81</td>
<td>0.81</td>
<td>15.24</td>
<td>3.66</td>
<td>0.03</td>
<td>1.16</td>
<td>3.09</td>
<td>3.73</td>
<td>3.53</td>
<td>0.16</td>
<td>98.22</td>
<td>2.48</td>
<td>75.80</td>
<td></td>
</tr>
<tr>
<td>66.33</td>
<td>0.62</td>
<td>15.60</td>
<td>3.68</td>
<td>0.08</td>
<td>1.11</td>
<td>3.17</td>
<td>4.13</td>
<td>3.27</td>
<td>0.22</td>
<td>98.21</td>
<td>2.48</td>
<td>75.80</td>
<td></td>
</tr>
<tr>
<td>Sample: R0mm-1</td>
<td>62.07</td>
<td>0.78</td>
<td>17.01</td>
<td>4.43</td>
<td>0.05</td>
<td>1.65</td>
<td>4.89</td>
<td>3.24</td>
<td>3.01</td>
<td>0.19</td>
<td>97.32</td>
<td>2.29</td>
<td>76.10</td>
</tr>
<tr>
<td>63.36</td>
<td>0.81</td>
<td>15.96</td>
<td>4.06</td>
<td>0.08</td>
<td>1.60</td>
<td>4.00</td>
<td>3.38</td>
<td>3.41</td>
<td>0.23</td>
<td>96.89</td>
<td>2.48</td>
<td>76.10</td>
<td></td>
</tr>
<tr>
<td>63.75</td>
<td>0.70</td>
<td>15.96</td>
<td>4.47</td>
<td>0.10</td>
<td>1.65</td>
<td>4.14</td>
<td>3.33</td>
<td>3.37</td>
<td>0.23</td>
<td>97.60</td>
<td>2.48</td>
<td>76.10</td>
<td></td>
</tr>
<tr>
<td>64.71</td>
<td>0.77</td>
<td>15.97</td>
<td>3.80</td>
<td>0.07</td>
<td>1.45</td>
<td>3.81</td>
<td>3.56</td>
<td>3.47</td>
<td>0.23</td>
<td>97.84</td>
<td>2.48</td>
<td>76.10</td>
<td></td>
</tr>
<tr>
<td>62.63</td>
<td>0.82</td>
<td>16.16</td>
<td>4.28</td>
<td>0.10</td>
<td>1.60</td>
<td>5.10</td>
<td>2.88</td>
<td>3.05</td>
<td>0.24</td>
<td>96.86</td>
<td>2.48</td>
<td>76.10</td>
<td></td>
</tr>
<tr>
<td>Sample: R2S1 (ol-rich)</td>
<td>67.01</td>
<td>0.74</td>
<td>14.78</td>
<td>3.37</td>
<td>0.07</td>
<td>1.03</td>
<td>2.75</td>
<td>3.69</td>
<td>3.82</td>
<td>0.20</td>
<td>97.46</td>
<td>2.57</td>
<td>67.30</td>
</tr>
<tr>
<td>67.81</td>
<td>0.81</td>
<td>14.84</td>
<td>3.06</td>
<td>0.07</td>
<td>0.95</td>
<td>2.78</td>
<td>3.70</td>
<td>3.87</td>
<td>0.22</td>
<td>98.11</td>
<td>2.57</td>
<td>67.30</td>
<td></td>
</tr>
<tr>
<td>68.32</td>
<td>0.73</td>
<td>14.98</td>
<td>3.39</td>
<td>0.07</td>
<td>0.96</td>
<td>2.93</td>
<td>3.64</td>
<td>3.85</td>
<td>0.24</td>
<td>99.11</td>
<td>2.57</td>
<td>67.30</td>
<td></td>
</tr>
<tr>
<td>Sample: R2S3 (hbl-rich)</td>
<td>65.03</td>
<td>0.78</td>
<td>15.48</td>
<td>3.79</td>
<td>0.10</td>
<td>1.83</td>
<td>3.78</td>
<td>3.36</td>
<td>3.15</td>
<td>0.16</td>
<td>97.46</td>
<td>2.34</td>
<td>74.30</td>
</tr>
<tr>
<td>66.53</td>
<td>0.78</td>
<td>15.53</td>
<td>3.71</td>
<td>0.11</td>
<td>1.26</td>
<td>3.37</td>
<td>3.70</td>
<td>3.47</td>
<td>0.20</td>
<td>98.66</td>
<td>2.34</td>
<td>74.30</td>
<td></td>
</tr>
<tr>
<td>66.48</td>
<td>0.78</td>
<td>15.58</td>
<td>3.80</td>
<td>0.10</td>
<td>1.22</td>
<td>3.32</td>
<td>4.00</td>
<td>3.24</td>
<td>0.24</td>
<td>98.76</td>
<td>2.34</td>
<td>74.30</td>
<td></td>
</tr>
<tr>
<td>Sample: R4S3 (brown pumice)</td>
<td>70.27</td>
<td>0.46</td>
<td>13.46</td>
<td>1.49</td>
<td>0.04</td>
<td>0.36</td>
<td>1.20</td>
<td>4.20</td>
<td>3.94</td>
<td>0.02</td>
<td>95.48</td>
<td>2.51</td>
<td>63.70</td>
</tr>
<tr>
<td>69.60</td>
<td>0.40</td>
<td>13.58</td>
<td>1.52</td>
<td>0.02</td>
<td>0.30</td>
<td>1.35</td>
<td>4.15</td>
<td>4.23</td>
<td>0.14</td>
<td>95.29</td>
<td>2.51</td>
<td>63.70</td>
<td></td>
</tr>
<tr>
<td>70.67</td>
<td>0.44</td>
<td>13.01</td>
<td>1.71</td>
<td>0.02</td>
<td>0.42</td>
<td>1.48</td>
<td>3.69</td>
<td>4.06</td>
<td>0.07</td>
<td>95.55</td>
<td>2.51</td>
<td>63.70</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Matrix glass compositions as determined by electron microprobe. Percent melt calculations by the method of Melson, 1983 (see text). KBu denotes bulk rock concentration of K taken from Table 3.

1. R0-W: 1985 white pumice
2. R0-G-1: 1985 gray pumice
3. R0mm-1: 1985 dark brown pumice
4. R2S1: olivine-rich pumice, eruption R2
5. R2S3: hornblende-rich pumice, eruption R2
6. R4S3: typical brown pumice eruption R4
<table>
<thead>
<tr>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>FeO*</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>P2O5</th>
<th>Total</th>
<th>KBu</th>
<th>% Melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>74.16</td>
<td>0.34</td>
<td>13.53</td>
<td>1.23</td>
<td>0.20</td>
<td>0.93</td>
<td>4.48</td>
<td>4.57</td>
<td>0.20</td>
<td>99.64</td>
<td>2.80</td>
<td>61.30</td>
<td></td>
</tr>
<tr>
<td>71.46</td>
<td>0.34</td>
<td>13.18</td>
<td>1.14</td>
<td>0.14</td>
<td>0.21</td>
<td>0.99</td>
<td>4.11</td>
<td>4.65</td>
<td>0.17</td>
<td>96.39</td>
<td>60.20</td>
<td></td>
</tr>
<tr>
<td>73.32</td>
<td>0.30</td>
<td>13.33</td>
<td>1.21</td>
<td>0.02</td>
<td>0.23</td>
<td>0.97</td>
<td>4.14</td>
<td>4.46</td>
<td>0.07</td>
<td>97.95</td>
<td>62.80</td>
<td></td>
</tr>
<tr>
<td>71.78</td>
<td>0.67</td>
<td>14.21</td>
<td>2.91</td>
<td>0.09</td>
<td>0.65</td>
<td>1.69</td>
<td>4.79</td>
<td>3.35</td>
<td>0.18</td>
<td>100.32</td>
<td>2.30</td>
<td>68.70</td>
</tr>
<tr>
<td>70.14</td>
<td>0.63</td>
<td>14.49</td>
<td>2.78</td>
<td>0.09</td>
<td>0.65</td>
<td>1.76</td>
<td>4.45</td>
<td>4.03</td>
<td>0.17</td>
<td>99.19</td>
<td>57.10</td>
<td></td>
</tr>
<tr>
<td>69.10</td>
<td>0.74</td>
<td>15.27</td>
<td>2.85</td>
<td>0.08</td>
<td>0.52</td>
<td>2.38</td>
<td>4.44</td>
<td>3.84</td>
<td>0.21</td>
<td>99.43</td>
<td>59.90</td>
<td></td>
</tr>
<tr>
<td>69.25</td>
<td>0.66</td>
<td>14.42</td>
<td>2.66</td>
<td>0.05</td>
<td>0.53</td>
<td>1.72</td>
<td>4.15</td>
<td>4.66</td>
<td>0.26</td>
<td>98.36</td>
<td>2.30</td>
<td>49.40</td>
</tr>
<tr>
<td>69.73</td>
<td>0.79</td>
<td>14.74</td>
<td>2.34</td>
<td>0.03</td>
<td>0.45</td>
<td>1.76</td>
<td>4.28</td>
<td>4.69</td>
<td>0.24</td>
<td>99.05</td>
<td>49.00</td>
<td></td>
</tr>
<tr>
<td>72.37</td>
<td>0.21</td>
<td>12.87</td>
<td>1.21</td>
<td>0.02</td>
<td>0.25</td>
<td>0.99</td>
<td>3.45</td>
<td>5.08</td>
<td>0.03</td>
<td>96.48</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>73.58</td>
<td>0.26</td>
<td>13.30</td>
<td>1.28</td>
<td>0.01</td>
<td>0.25</td>
<td>0.94</td>
<td>3.83</td>
<td>4.97</td>
<td>0.05</td>
<td>98.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.32</td>
<td>0.31</td>
<td>13.62</td>
<td>1.69</td>
<td>0.06</td>
<td>0.38</td>
<td>1.80</td>
<td>4.50</td>
<td>2.84</td>
<td>0.08</td>
<td>98.60</td>
<td>1.87</td>
<td>65.80</td>
</tr>
<tr>
<td>73.21</td>
<td>0.31</td>
<td>13.81</td>
<td>1.69</td>
<td>0.08</td>
<td>0.39</td>
<td>1.88</td>
<td>4.33</td>
<td>3.15</td>
<td>0.06</td>
<td>98.91</td>
<td>59.40</td>
<td></td>
</tr>
<tr>
<td>72.22</td>
<td>0.23</td>
<td>13.31</td>
<td>1.55</td>
<td>0.09</td>
<td>0.39</td>
<td>1.89</td>
<td>4.02</td>
<td>3.19</td>
<td>0.08</td>
<td>96.88</td>
<td>58.60</td>
<td></td>
</tr>
<tr>
<td>66.25</td>
<td>0.76</td>
<td>15.05</td>
<td>2.80</td>
<td>0.07</td>
<td>0.89</td>
<td>2.98</td>
<td>3.85</td>
<td>3.35</td>
<td>0.17</td>
<td>96.20</td>
<td>2.12</td>
<td>62.70</td>
</tr>
<tr>
<td>67.30</td>
<td>0.48</td>
<td>14.95</td>
<td>2.34</td>
<td>0.01</td>
<td>0.72</td>
<td>2.29</td>
<td>4.46</td>
<td>3.52</td>
<td>0.16</td>
<td>96.23</td>
<td>59.10</td>
<td></td>
</tr>
<tr>
<td>66.40</td>
<td>0.54</td>
<td>14.90</td>
<td>2.79</td>
<td>0.07</td>
<td>0.86</td>
<td>2.74</td>
<td>3.96</td>
<td>3.58</td>
<td>0.22</td>
<td>96.06</td>
<td>58.10</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 (cont.)

7. R4 banded pumice: unmixed black and white pumice bands in a single lump, eruption R4
8. R5S33: microscopically heterogeneous R5 pumice lump with enclaves of microlite-poor pumice with biotite
9. R6S9: hornblende-rich R6 pumice
10. R8S5: typical brown pumice, eruption R8
Figure 23. Matrix glass and whole rock (bulk pumice) compositions of Ruiz tephra plotted onto the geohygrorometer of Merzbacher and Eggler (1984). (a.) R0 (b.) R2 (c.) R4 (d.) R5 (e.) R6 (f.) R8
Figure 23. (cont.)
Figure 23. (cont.)
Figure 23. (cont.)
Figure 23. (cont.)
Figure 23. (cont.)
light of the complex zoning preserved within phenocrysts and evidence for mixing and assimilation of different magma batches. Melson et al. (1990) also report a wide range of water contents (1-4%) for the 1985 pumices using this method and estimate last mineral-melt equilibration at depths as shallow as 1-3 km.

For eruption R2, two separate lumps of pumice were analyzed in an attempt to quantify some subtle differences in petrographic character between these samples. Thin section sample R2S1 (Figure 23b, Table 4) has hornblende as a minor stable phase (approximately 1 volume percent) with no olivine present, while sample R2S3 contains only one small, corroded hornblende crystal with a reaction rim, and has numerous olivine xenocrysts (less than 1 volume percent). Matrix glass compositions show about a 2% difference in silica content between these two pumice types, but estimated water contents are approximately equal at about 1%. For sample R2S1, matrix glass compositions do not plot within the hornblende stability field (stippled area) of Figure 23b, yet hornblende is found as a stable minor phase in this sample. A hypothetical path from R2 whole rock compositions to R2S1 matrix glass may have involved an excursion up into or near the hornblende stability field in a manner similar to the hypothesized pre-eruptive melts for Mount St. Helens (Merzbacher and Eggler, 1984). Once crystallized, these hornblende phenocrysts may be able to persist out of the stability field as volatile exsolution (boiling) produces overpressures within the magma chamber just prior to eruption.

The only megascopically-banded pumice that did not belong to the R0 eruption (1985) was found as a single lump within eruption layer R4 (Figure 24). Because color in the Ruiz pumices is a crude indicator of silica content, the initial interest in this rock was in the black band, which is the darkest sample of Ruiz tephra we have yet located. The petrographic differences which describe the black and white bands of this sample are essentially the same as those which describe the dark and light tephras of 1985, with a few exceptions. The black band is characterized by high crystallinity (abundant
Figure 24. Banded pumice, eruption R4.
microlites), sieve-textured plagioclase, nearly opaque and poorly vesiculated glass, olivine xenocrysts and abundant hornblende. The white band has fewer, larger crystals, no microlites and well-formed bubble walls of translucent glass, but unlike the 1985 white pumice, no biotite. Whole rock analyses of carefully separated samples of the black and white pumice bands reveal that the black band is similar to other pumices (R8, R1, R0-G) in terms of silica content (62 wt. %), and the white band is slightly lower in silica and potassium (65 and 2.8 wt. %, respectively) than the 1985 pumices. For eruption R4, matrix glasses from the nominal brown pumice as well as the black and white portions of the R4 banded pumice were analyzed (Figure 23c, and Table 4). Estimated water contents for the R4 pumice is generally higher (2-3%) than the R0 and R2 pumices, with the brown pumice and bulk rock compositions falling just above the 2% contour. The banded pumice glasses show slightly higher estimated water contents that are out of the calibrated field, but probably in the 3-4% range. For the black band, matrix glasses are slightly less-evolved (a smaller q+ or component) than the nominal R4 brown pumices (which have higher bulk rock silica), but are more evolved than the glasses of other pumices with similar bulk rock silica (R0-G, R8).

The apparent explanation for both the evolved matrix glass compositions and the unusually dark color of the black band in this sample is the high degree of crystallinity reported in the "percent melt" calculations in Table 4. Various color differences in these pumices seem to be more a function of the overall crystallinity of the samples than chemical character or water content.

A single, megascopically homogeneous lump of brown pumice from eruption R5 (Sample R5S33) was found to be petrographically identical to the typical banded pumices of the 1985 deposit that contained unmixed streaks of dark brown and white, biotite-rich tephra. Matrix glass compositions for the separate bands in Sample R5S33 give water content estimates of 2.3% H2O and reveal a large compositional gap between the magma types (Figure 23d). Glass from the biotite-rich enclaves (microlite-
poor band) is very similar compositionally to the 1985 white pumice glass with the only other K₂O content as great as 5% (Table 4).

Matrix glass within a sample of the anomalous R6 pumice, which always contains abundant euhedral hornblende, was analyzed to determine if compositions would plot within the hornblende stability field for the geohygro meter (Figure 23e). Analyses plot below the calibrated portion of the hornblende field at about 3% H₂O, but melts may have passed through or resided in this field shortly before eruption and final crystal growth, or been overpressured as mentioned earlier. Silica contents of R6 matrix glass are similar to R0 white pumice glasses (Table 4), but K₂O contents reveal the anomalous low-K character of the R6 magma seen in whole rock compositions. Water contents for the R8 pumice melt is estimated to be between 1 and 2% (Figure 23f). Bulk pumice data for R8 shows the highest water content and least differentiation of all bulk rocks plotted, while matrix glasses are slightly more evolved than the dark brown or gray pumices of R0.

Burnham (1972, in Cas and Wright, 1987) has shown that andesitic magmas with 1-4 wt.% water will become saturated with respect to water at 0.5 to 3.6 km below the surface of the earth, and any further rise, crystallization, or cooling of these magmas can produce a potential increase of 53 volume percent by secondary boiling. All seismicity prior to the 13 November, 1985 eruption occurred within about 7 km of the surface, and a swarm of strong earthquakes on 7 and 8 November, 1985 were located at depths of between 3 and 5 km beneath the crater (Williams and Meyer, 1988), probably signalling a major event within the upper-level magma chamber.

**DISCUSSION- PETROGENESIS OF THE RUIZ PUMICES**

The generation of magma as crust is subducted beneath a continental margin and the processes which determine the geochemical character of the wide variety of igneous rocks found on or near the surface of the earth above these zones is, to say the least,
the subject of much debate. The case for Nevado del Ruiz is no exception. Uniform Sr ratios led Thorpe et al. (1984) to discount crustal contamination in Ruiz magmas. Vatin-Perignon et al. (1990) note that the restricted range of Sr isotope values obtained from the Ruiz volcanic suite is very similar to those of the Jurassic Ibague batholith, which intrudes the metamorphic basement of the area, but based on the REE chemistry, also find little to no crustal contamination of the parental Ruiz magma. Their calculated fractional crystallization path from a basaltic Ruiz lava to a daughter composition of a Ruiz dacite requires removal of about 75 wt.% crystals of plagioclase, clinopyroxene, orthopyroxene, magnetite and ilmenite. Modeling with amphibole in the later stages of the fractionation calculations was found to produce unrealistic results.

In contrast, preliminary studies of the Sr, Nd, and oxygen isotopes of the NVZ, and Ruiz in particular, have led others to invoke significant crustal contamination of magmas during ascent (Harmon and Hoefs, 1984; James and Murcia, 1984). Similarly, Melson et al. (1990) find the high Ba, Th, U, and K/Rb ratios of the 1985 pumice may reflect crustal contamination, noting the relatively thick crust beneath Ruiz and previous studies which have correlated enrichment of these elements with crustal thickness. This same study also finds that the major element variation within the 1985 pumices can be accounted for by simple crystal fractionation of about 25 wt.% plagioclase and 9 wt.% combined hypersthene and olivine. Sigurdsson et al. (1990) also have modeled the 1985 tephra with similar results, so it is fairly clear that whether the parental Ruiz magmas were contaminated by continental crust or not, the later development of these melts was dominated by simple crystal fractionation.

Similar debate over the role of magma mixing in triggering the eruption of 1985 has resulted in several models of the pre-eruptive Ruiz magma system, depicting possible scenarios which explain the heterogeneous deposit, mineral disequilibria, and eruption style. Citing the work of Sparks and Sigurdsson (1977), magma mixing proponents envision an intrusion of hot magma at the base of a zoned magma chamber which sets
up a convective cell followed by an increase in volume and pressure, then fracture and eruption. Olivine xenocrysts, high-Mg pyroxenes, and glomerophyric crystal aggregates are cited as the only remaining evidence of a more basic end-member magma which evolved more rapidly toward an andesitic composition than the dacitic magma it was mixed with, in the manner predicted by the experiments of Kouchi and Sunagawa (1985). Mixing is thought to have been interrupted before complete homogenization was attained, resulting in a heterogeneous deposit and some banded pumices. The advantage of a mixing model hypothesis for the Ruiz tephra, besides providing a trigger mechanism for the eruption, lies in its ability to explain the observed textural heterogeneities and disequilibrium relationships between phenocrysts and melt. Banded pumices, xenocrysts with reaction rims, and sieve-textured plagioclase are commonly attributed to magma mixing (Al-Rawi and Carmichael, 1967; Cantagrel et al., 1984; Sakuyama, 1984; Sigurdsson and Sparks, 1981).

On the basis of finding a compositional gap from 67 to 71 wt.% SiO2 in matrix glasses from the 1985 deposit, Sigurdsson et al. (1990) suggest that magma mixing was not an important factor prior to eruption, and that mixing may have taken place only within the conduit during ascent. They propose a two-layer system of a lower andesitic magma overlain by a dacitic magma, each layer convecting independently within itself and dominated by a separate liquid composition. In this scenario, melt inclusions which were found to span the compositional gap in matrix glass compositions are attributed to the random trapping of liquids at various stages of evolution near a thermal boundary layer at the margins of the andesitic layer. Plagioclase crystals are proposed to have been exchanged between layers at the horizontal boundary by gravitational settling or erosion and entrainment along the outside margins. Our study fails to support the assertion that there is a gap in matrix glass compositions from 67 to 71 wt.% SiO2 (see sample R0-G-1, Table 4, also
unpublished data), which corroborates our finding no compositional gaps in whole rock compositions. Other studies have also reported matrix glass compositions which fall within this range, but they are few in number (Gorgaud and Thouret, 1990; Melson et al., 1990). We also feel that this model fails to transfer enough sodic plagioclase into the andesitic layer to account for the abundant sieve-textured plagioclase found in these rocks. Melson et al. (1990) also establish that crystal settling rates in magmas of effective viscosities like those of the 1985 bulk magmas are insignificant, implying at least limited mixing along layer boundaries to introduce sodic plagioclase into the andesite.

It is our conclusion that the pumices of the Nevado del Ruiz sequence, especially the most recently erupted examples, are comngled magmas according to the definition of Sparks and Marshall (1986). That is, these rocks are mixtures of separate magmas which are not completely homogenized, but which display a range of liquid compositions, temperatures, rheologies, and water contents. The abundance of resorbed sodic plagioclase suggests a significant contribution from the dacitic magma, but we are surprised not to have found more corroded biotite along with the sodic plagioclase. Some of the most evolved tephras (the white pumices) are not comngled, but probably represent the acid end-member involved in the mixing event. These melts probably originated along the margins of a partially crystallized andesitic magma body and migrated towards the top of the magma chamber. McBirney et al. (1985) have shown that calc-alkaline melts become less-dense with increasing fractionation, so that any liquids produced by the fractionation of crystals within or at the margins of a magma body should be able to rise and accumulate despite the increase in density associated with a decrease in temperature. Once separated from the hotter, drier andesitic magma body, the fractionated liquid may have experienced relatively slow, uninterrupted crystal growth (large, euhedral crystals in white pumice) which may have been buffered by higher water contents of approximately 4 wt.%. The most differentiated liquids
accumulated at the coolest uppermost margins of the magma chamber roof, producing
the biotite-bearing white pumices with matrix glasses containing approximately 74 wt.%
SiO$_2$ and 5 wt.% K$_2$O. Analyses and descriptions for other white pumices from the
1985 eruption reported in the literature (sometimes referred to as pale gray pumices)
reveals that all samples do not contain biotite, and that the dacitic magma may have been
slightly zoned compositionally, with about a 2 wt.% range in SiO$_2$ and a 0.5 wt% range
in K$_2$O content. This dacite cap may have been collecting in the upper regions of the
magma chamber since eruption R1 and during the entire magma chamber recharge
process, becoming slightly zoned as it was continuously fed from below. Growth of
crystals and a decrease in temperature of about 75°C in the dacitic magma (Table 2)
may have increased the contrast in viscosities between the upper and lower levels of the
chamber to the point that different magma batches were effectively separated by their
rheologies. The temperature difference and crystallization of the dacitic magma may also
have begun to work in opposition to the decrease in density associated with fractionation
that allowed liquid to migrate upward. Attempts by the magma system to respond to
small changes in density by allowing less-dense material to rise and more-dense material
to sink may be eventually slowed or interrupted by an increasing rheological contrast
between the upper and lower levels, decreasing the stability of the density stratification
within the magma chamber.

In our scenario, a model of the upper pre-eruptive magma system for the 1985
event would include a relatively small, vertically-elongate magma chamber at depths
of between 3 and 5 km beneath the summit, dominated by two separate compositional
zones. The lower zone is composed of an acid andesite magma at about 925°C with
water contents of 0 to 2 wt. percent, similar to batches of magma which have fed prior
eruptions and been replenished from a deeper magma reservoir through time. The upper
zone consists of a smaller, but growing volume of cooler, viscous dacitic magma at
about 850°C and with 3-4 wt.% water, slightly zoned compositionally, and derived
from the andesite below by crystal fractionation, but now effectively separated by a compositional gap that is maintained by the contrasting rheologies of the two layers which acts as a barrier to mixing, perhaps in spite of decreasing gravitational stability.

Subsequently, we envision the input of a hotter, slightly more basic magma which is intruded from below into the base of the andesite layer. This hotter magma evolves quickly and completely toward an acid andesite bulk composition, but is only recorded by olivine xenocrysts, high-Mg pyroxenes, and perhaps cumulophyric crystal aggregates. The input of thermal energy into the acid andesite layer may have been sufficient to suddenly reverse the density stratification of the magma chamber, causing some volume of the lower, most dense and crystal-rich portion of the dacitic magma to founder downward and be replaced by hotter, buoyant acid andesite. Assimilation of the dacitic magma parcel by the larger andesite body may have induced the secondary growth of microlites in the andesite, transferred large numbers of sodic plagioclase to the andesite, and produced a small population of pumices with intermediate whole rock and matrix glass compositions.

Alternatively, a vigorous convection cell established within the andesitic layer may have been able to disrupt the boundary layer with the upper layer sufficiently to erode and entrain enough dacitic magma to produce the same results, but at a slower rate. Secondary boiling of the andesitic magma may have provided the necessary excess volatile pressure to breach the confining carapace and initiate the eruption. Incomplete mixing of magma batches prior to eruption brought diverse magma types from different levels within the magma chamber into contact during the eruption in the manner described by Blake (1981), perhaps facilitating more mixing, but also producing the wide range of colors and textures seen in the banded pumices. The variety of eruptive styles which were manifest in the 1985 eruption (plinian column, pyroclastic flows, and base surges) are best explained in terms of changing magma compositions and volatile content as the eruption progressed.
The suggested caldera at Nevado del Ruiz implies the existence of a large, near-surface magma chamber confined by the proposed caldera boundary fault system, possibly in the 5 to 7 km depth range beneath the summit. A large, crystallizing magma body is a convenient source for rising melts which could replenish discharged magmas or provide thermal input in the form of rising blebs of basic magma. It is also an attractive explanation for the unusually high volumes of SO2 which have continued to be discharged from Ruiz since the 1985 eruption. The rising plume from the magma reservoir and the active magma chamber beneath the Arenas crater is only one of many separate conduits and chambers which have fed the various volcanic centers which make up the Ruiz complex. The low K2O trend exhibited by the R6 pumice and various dome rocks are evidence of complexities which cannot be explained by a simplistic model of this volcano.

Our magma system model for Nevado del Ruiz must be modified when the petrographic character and eruption dynamics (volumes, intensities) of the pre-1985 eruptions are considered. The most obvious difference between the tephra of 1985 and the buried pumices we studied is the greater diversity of the 1985 products. With the realization that volumetrically minor samples such as banded pumices may be more difficult to locate after burial, we were nonetheless surprised to find only one megascopically banded pumice and one microscopically banded pumice in the course of several months of hand picking hundreds of pumice lumps from each of the pre-1985 deposits, and examining nearly one hundred thin sections in the laboratory. Although the processes which produced the diverse tephra of 1985 may have also been at work during prior eruptions, we feel that they were not as important as they were during the 1985 event, and that the volcano has undergone a fundamental change, with respect to eruptive products. This change may be related to the apparent recent input of a more basic magma into the magma system. Although more samples are needed to clearly define relationships through time, our samples from all pre-1985 deposits are
truly random, and there is a clear suggestion that the pumices are becoming more basic with time from eruptions R4 to R0, which correlates with an increase in eruption frequency (Figure 18). Clearly, Mg, Ca, Ni, Cr, and V are much higher for the dark brown and gray pumices of R0 than for the rest of the sequence, and this correlates with the observation that more olivine and glomerocrysts are observed in the most recent pumices, suggesting an increasing influence of a more basic magma upon the upper level magma chamber. In this light, the olivine xenocrysts and glomerocrysts cited as evidence of a thermal "trigger" for the 1985 eruption are seen as a relatively recent phenomenon in the Ruiz sequence, and can not be so readily invoked for earlier eruptions, especially R7 and R8, where no olivine and few glomerocrysts were noted in thin section.

If the 1985 activity is unusual, what are the implications for the magma system model we have proposed to explain the diversity of the 1985 tephra? In Part Two of this study, the eruption dynamics and physical characteristics of each deposit will be examined and combined with the petrologic information to produce a comprehensive model of the volcano based on the cumulative information we have for the entire sequence.
PART TWO: ERUPTION DYNAMICS

INTRODUCTION

Recent advances in the study of the controls and dynamics of volcanic eruption columns have provided volcanologists with the necessary tools to reconstruct the physical eruptive conditions of plumes and classify eruptions based on some simple fall deposit characteristics which can be easily measured in the field (Wilson et al., 1978; Carey and Sparks, 1986; Sparks, 1986; Pyle, 1989). The numerous tephra layers exposed on the flanks of Nevado del Ruiz present an unusual opportunity to apply these new techniques to a series of eruptions from a single volcano through time. The purpose of the second part of this study is to characterize and compare the physical characteristics of the eruptions which produced the most recent tephra deposits at Nevado del Ruiz. Physical parameters such as volume, column height, dispersal axes, eruptive style, duration and explosivity will be presented for eruptions R8-R0. A systematic study of this series of eruptions will be of general interest because it documents the recent eruptive history at this volcano and will be able to scale the disastrous eruption of 1985 against activity of the recent past. Additionally, information concerning the dispersal axes of earlier eruptions and the accumulation of volcanic ash through time can be used to improve ashfall hazard assessment at Ruiz. Current ashfall hazard maps for Ruiz are based on incomplete field information about the distribution of the tephra layers described in this study, and are biased by the 1985 eruption. A new ashfall accumulation map of the Ruiz deposits is presented which depicts the axis of maximum accumulation through time. Finally, a tentative model of Nevado del Ruiz which incorporates the recent eruptive and petrologic history of this volcano as determined by this study will be presented.

FIELD METHODS AND ANALYTICAL PROCEDURES

Tephra deposits R8-R0 were studied at approximately thirty locations around the
volcano. Thicknesses of individual deposits were measured, as were the maximum
diameters of the five largest pumice and lithic fragments found in each layer. For layer
R6, which does not usually contain pumice, only lithic fragments were measured.
Averages of the five largest pumices and lithics were used to construct isopleth maps
for each eruption (Appendix 3). Bulk samples were collected at approximately half of t
he locations for laboratory sieving. Because of the small volumes of these deposits and
their compaction, representative bulk samples were difficult to obtain. All median
grain size determinations (Appendix 3) must be considered to be biased towards smaller
diameters because of the natural tendency for pumice to be broken both during the
process of deposition/compaction and during an often difficult removal from the outcrop.
Procurement of reliable bulk samples of the 1985 deposit was found to be infeasible.
Often present as only a thin veneer of scattered pumices within the tall grasses, the
small volume and limited dispersal of the 1985 deposit made true grain size
determinations impossible. Eruption R1 (1845) is present as discontinuous stringers
of pumice within the living roots of vegetation upon the present-day surface and cannot
be sampled reliably. Layer R6 showed no significant median grain size variation over
the sample area (1.2 $\phi$ to 1.9 $\phi$ ;0.26 to 0.44mm). Therefore, grain size maps could not
be constructed for eruptions R0, R1, and R6. Isopach, maximum pumice and lithic
isopleth were drawn by visual best-fit of the field data, emphasizing smooth contours
and minimum values for data points. Median grain size maps were constructed in the
same manner after samples were air-dried and sieved in the laboratory using a nest of
sieves with a 1$\phi$ interval from 4$\phi$ to -4$\phi$ (1/16 mm to 32mm). Clasts larger than -4$\phi$
were separated by hand. Median grain size and sorting were calculated following the

VOLUMES

Isopach maps for each eruption were constructed and areas within individual
contours were measured (Appendix 3). Volumes were calculated using the method of Pyle, 1989, which plots ln thickness (of each isopach) versus (area within the isopach)\(^{1/2}\), so that for each eruption, \(V=13.08 T_0(b_t)^2\), where \(T_0\) is the extrapolated maximum deposit thickness, or the y-intercept (point of zero area coverage) of the line formed by plotting ln thickness on the ordinate and (area)\(^{1/2}\) on the abscissa, and \(b_t\) is the thickness half-distance. The thickness half-distance is calculated from the same line using the equation \(b_t=\ln2/k(\Pi)^{1/2}\), where \(k\) is the slope of that line. Calculated volumes for the Ruiz tephra layers were found to range from 1.9 to 29.5 \(\times 10^{-2}\) km\(^3\) and are listed in Table 5.

Because of their small volumes, compaction, and limited exposures at distances greater than 10 kilometers from the crater, the volumes calculated must be considered to be minima. Although the ln thickness versus (area)\(^{1/2}\) produced simple linear trends for the proximal deposits, there is some suggestion from these plots that the distal portions of these deposits may be characterized by a second, less-steeply sloping line (Figure 25). Since the bulk of any deposit lies within the fine fraction, small changes in the slope of the ln thickness versus (area)\(^{1/2}\) line can cause large differences in calculated volumes if the inflection point occurs beyond the proximal measurements used to define the line.

Airfall tephra layers of this magnitude (total volume) are seldom reported in the literature. Reasons for this include the fact that tephra layers of such small volumes are not widely distributed and exposed for study in the rock record. The remarkable preservation and accessibility of these layers at Ruiz make it a unique example in this respect. Similar volumes for historic pumice eruptions are reported for Usu volcano in 1977 (Katsui et al., 1978) and the May 25, 1980 eruption of Mt. St. Helens (Pyle, 1989), but it should be noted that these examples were probably sub-plinian in nature.

The data for the isopach map of eruption R6 was found to most easily conform to
Figure 25. Plot of $\ln$ thickness versus $(\text{area})^{1/2}$ for eruption R8. Data for the solid line described by the equation shown is from the R8 isopach map in Appendix 3 and demonstrates the method of Pyle (1989), which was used to calculate volumes. Dashed line shows possible slope for the distal portion of the deposit volume.
contours which did not seem to close upon the summit region of Nevado del Ruiz and the active Arenas crater. Similarly, maximum lithic isopleths for R6 are centered west of the summit region (Appendix 3). The centers of data for the isopach and lithic isopleth maps fall very near the location of the inactive crater, La Olleta (Figures 2, 4). We have previously documented the uniqueness of the R6 layer in comparison to the main Ruiz sequence in terms of outcrop appearance, petrographic and petrologic characteristics. Based on the cumulative knowledge of R6, it seems likely that this deposit originated not from the Arenas crater, but from La Olleta. The fine grainsize of the R6 material, abundance of lithic fragments, and dearth of juvenile material (pumice), seem to suggest that this may have been a phreatomagmatic eruption. However, the unimodal distribution and relatively well-sorted nature of this deposit (average sorting 1.6 φ for R6, compared to 2.8, 2.5, 2.2, 2.1, and 2.6 φ for eruptions R2, R4, R5, R7, and R8, respectively) would argue against a phreatoplinian origin since those deposits are described as being generally poorly-sorted despite a fine medium grainsize, and bimodally distributed (Self and Sparks, 1978; Walker, 1981; Cas and Wright, 1987). R6 does not contain accretionary lapilli, but lapilli are generally reported in association with phreatomagmatic eruptions that involve large amount of water such as those present in calderas or crater lakes. Any phreatomagmatic eruption from La Olleta would probably involve much less water, such as that present as meltwater from snow and ice. It is perhaps most interesting to discover that La Olleta was possibly active as little as about 1500 years ago (Figure 6).

COLUMN HEIGHTS

Recent theoretical modeling of volcanic plumes and comparisons with observations of historic eruptions has provided a basis for estimating total column height and crosswind velocity based on the size and shape of maximum clast isopleths (Carey and Sparks, 1986). To avoid ambiguities associated with the density variation and fracture of pumice clasts, lithic isopleth maps were used to estimate column heights and wind
velocities for eruptions R8-R0. These lithic isopleth maps were characterized in terms of maximum downwind range from the Arenas crater (or La Oletta) and maximum crosswind range half-distance (isopleth half-width) for either the 3.2 cm diameter (R0, R2, R4, R7, R8) or the 1.6 cm diameter isopleth (R1, R5, R6). Results of our modeling are plotted on the appropriate diagram from Carey and Sparks (1986) along with their data for three other well-studied eruptions for comparison (Figure 26). Estimated column heights for the Ruiz eruptions range from 18.1 to 26.0 km and are reported in Table 5.

Sparks (1986) has used numerical calculations to relate column height and magma temperature to mass discharge rate. Mass discharge rates and volume discharge rates were graphically determined by using the estimated column height for each eruption and an eruption temperature of 925° (based on our geothermometry in Part 1) on the theoretical curves of Sparks (1986) derived for a tropical atmosphere, assuming a magma density of 2500 kg/m³. Eruption durations were calculated by dividing the total mass of each deposit as determined from our volume estimates by the appropriate mass discharge rate, assuming this rate to be the average during the eruption. Mass discharge rates, volume discharge rates, dense rock equivalent volumes (DRE), and eruption durations are presented in Table 5. Eruption durations and DRE volumes must be considered to be minima since their calculation involves our estimates of deposit volumes which are minima and assumes the mass discharge rate to be an average, when it is actually a peak value for these conditions because it is based on the maximum estimated column height.

ERUPTION CLASSIFICATION

Different classification schemes for eruptions based on the characteristics of airfall deposits have been used as a frame of reference to describe eruptive style and convey a sense of scale for comparative purposes (Walker, 1973, 1980; Newhall and Self,
Figure 26. Column height determinations for the Ruiz eruptions using the method of Carey and Sparks, 1986. Diagrams are contoured in column height (km) and wind velocity (m/s). Eruptions were modeled based on the lithic isopleth maps in Appendix 3.
<table>
<thead>
<tr>
<th>Eruption</th>
<th>Col. Height (km)</th>
<th>Volume (km³)</th>
<th>DRE Vol (km³)</th>
<th>T.E.M.(kg)</th>
<th>V.D.R.(km³/s)</th>
<th>M.D.R.(kg/s)</th>
<th>E.D. (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>26.0</td>
<td>0.02</td>
<td>7.4 x 10⁻³</td>
<td>1.8 x 10¹⁰</td>
<td>1.6 x 10⁻⁵</td>
<td>3.9 x 10⁷</td>
<td>21</td>
</tr>
<tr>
<td>R1</td>
<td>18.1</td>
<td>0.06</td>
<td>2.2 x 10⁻²</td>
<td>5.5 x 10¹⁰</td>
<td>5.3 x 10⁻⁶</td>
<td>1.3 x 10⁷</td>
<td>189</td>
</tr>
<tr>
<td>R2</td>
<td>25.7</td>
<td>0.16</td>
<td>5.9 x 10⁻²</td>
<td>1.5 x 10¹¹</td>
<td>1.4 x 10⁻⁵</td>
<td>3.6 x 10⁷</td>
<td>190</td>
</tr>
<tr>
<td>R4</td>
<td>21.2</td>
<td>0.17</td>
<td>6.2 x 10⁻²</td>
<td>1.6 x 10¹¹</td>
<td>7.9 x 10⁻⁶</td>
<td>2.1 x 10⁷</td>
<td>359</td>
</tr>
<tr>
<td>R5</td>
<td>24.5</td>
<td>0.05</td>
<td>1.8 x 10⁻²</td>
<td>4.6 x 10¹⁰</td>
<td>1.2 x 10⁻⁵</td>
<td>3.2 x 10⁷</td>
<td>69</td>
</tr>
<tr>
<td>R6</td>
<td>21.5</td>
<td>0.08</td>
<td>3.0 x 10⁻²</td>
<td>7.6 x 10¹⁰</td>
<td>8.3 x 10⁻⁶</td>
<td>2.2 x 10⁷</td>
<td>161</td>
</tr>
<tr>
<td>R7</td>
<td>22.2</td>
<td>0.17</td>
<td>6.2 x 10⁻²</td>
<td>1.6 x 10¹¹</td>
<td>9.1 x 10⁻⁶</td>
<td>2.5 x 10⁷</td>
<td>311</td>
</tr>
<tr>
<td>R8</td>
<td>25.1</td>
<td>0.29</td>
<td>1.1 x 10⁻¹</td>
<td>2.7 x 10¹¹</td>
<td>1.3 x 10⁻⁵</td>
<td>3.3 x 10⁷</td>
<td>372</td>
</tr>
</tbody>
</table>

Table 5. Summary of Individual Eruption Dynamics

1. DRE = dense rock equivalent
2. T.E.M. = total erupted mass
3. V.D.R. = volume discharge rate
4. M.D.R. = mass discharge rate
5. E.D. = eruption duration (calculated by volume, and rounded to nearest minute)
1982; Carey and Sigurdsson, 1989; Pyle, 1989). Three methods were chosen to describe and classify the Ruiz eruptions. The first is the VEI (Volcanic Explosivity Index) of Newhall and Self (1982) as modified by Carey and Sigurdsson (1989) to show the relationship between VEI and a plot of column height versus total erupted mass (Figure 27). As a widely used basis for the comparison of eruptions, the VEI scales eruptions based both their dispersive power (column height) and magnitude (total erupted volume). On this basis, the Ruiz eruptions are classified as 3 on the VEI scale, except for R8, which plots as a 4. The data that must be classified as a VEI of 3 actually plot outside the limits of the numbered fields, and have column heights which are comparable to events which are classified with VEI's of 4 or 5. This may reflect an underestimation of volumes for these deposits as discussed earlier. However, Carey and Sigurdsson (1989) document similar results for other eruptions, perhaps reflecting the arbitrary nature of classification in general, and the need for revision of the VEI fields. We support the suggestion of Carey and Sigurdsson (1989) that specific eruption parameters such as magnitude and intensity should be reported whenever possible.

Walker (1980) has compiled area plots for plinian pumice deposits documenting the areas enclosed by isopleths of median grainsize, maximum average pumice and lithic diameters. Figure 28 plots the Ruiz data against the fields suggested by the area plots of the plinian eruptions studied by Walker. All eruptions fall within the plinian field for maximum lithics, except R6 and R1, which plot as subplinian. Maximum pumice data for all the Ruiz eruptions plot nearer the plinian-subplinian boundary and median grainsizes for all the available Ruiz data plots well below the plinian field. The seemingly systematically decreasing plinian character of the Ruiz maximum pumice and median grainsize data probably reflects the tendency for pumices to break during the processes of deposition and compaction, and specifically, the difficulties associated with obtaining reliable bulk samples from outcrop, as previously discussed. Assuming
Figure 27. VEI determinations for the Ruiz eruptions (after Newhall and Self, 1982).
Figure 28. Ruiz data for median grainsize (Md), maximum pumice (MP) and maximum lithics (ML) plotted with the plinian fields (stippled areas) suggested by the data of Walker, 1981.
the Ruiz lithic data to be the most representative measure for these eruptions, comparison with Walker's data suggests that with the exception of R6 and R1, these eruptions were true plinian events, and that maximum pumice and median grainsize isopleths are probably drawn too conservatively. Alternatively, it should be noted that these pumices are very crystal-rich, often 30 to 40 volume percent (Table 4), while pumices typically described in the literature and used for dispersal studies usually contain less than 10 volume percent crystals. Since vesiculation is often seen to be initiated at the surface of crystals, which increase magma viscosities, the relatively fine-grained nature of these deposits may represent increased fragmentation due to the viscous nature of the crystal-rich Ruiz magmas.

The third classification scheme we have employed is that of Pyle (1989), which broadly conforms to the classification scheme of Walker (1973), but is more widely applicable to situations where detailed and reliable grainsize analyses along the dispersal axes are not available. This method uses a plot of the thickness half distance, \( b_t \) (as determined in the volume calculations), versus the half-distance ratio \( b_c/b_t \) where \( b_c \) is calculated from the equation \( b_c = \ln(2)/k_c(\Pi)^{1/2} \) and \( k_c \) is the negative value of the slope of the line formed by a plot of \( \ln \) (maximum clast isopleth) versus (area within the isopleth)\(^{1/2} \). Results for the Ruiz data are presented in Figure 29, and show that except for R1 and R6, all other eruptions plot well within the plinian field. It should be noted that underestimates of volumes due to compaction or other factors may tend to decrease \( b_t \) and move data points toward the left margin of the graph and closer to the sub-plinian field.

**DISCUSSION OF RUIZ ERUPTION DYNAMICS**

Examination of the results presented in Table 5 reveals that the recent eruptive history of Nevado del Ruiz has involved a series of similar eruptions that have been significant column heights, and small eruptive volumes. Wadge (1977, 1982) has shown that some
Figure 29. Classification of the Ruiz eruptions using the scheme of Pyle (1989). Numbers on graph represent eruptions R8-R0.
volcanoes erupt magmas at rates which, on average, are constant over periods of time. A plot of cumulative volume erupted versus time for the main Ruiz sequence is presented in Figure 30. The Ruiz series of eruptions and intervening repose periods produce a sawtooth curve which defines a mean (dotted line in Figure 30). Based on the slope of the mean in Figure 30, the effusion rate for Ruiz is approximately 0.33 km$^3$ per thousand years. Assuming a constant supply of magma, then, in general, one could expect short repose periods to precede small-volume eruptions, and longer repose periods to precede relatively larger-volume eruptions. The data in Figure 30 do not seem to support the idea of a constant magma supply at Ruiz. The true volume versus time relationship is made uncertain by the exclusion of R9 from this study and the exclusion of R6 from Figure 30, which is intended to include only deposits from the Arenas crater. However, in general, for this most recent series of deposits, Figure 30 demonstrates that there seems to be little correlation between repose period and erupted volume at Ruiz. It should be noted that eruption R8, which has the largest estimated volume of the sequence, does follow a long repose period after R9 (approximately 6000 years), and volumes do decrease with increased eruption frequency after eruption R2. A hypothetical mean drawn for eruptions R4 - R0 would be much steeper than the average gradient for the entire sequence, and may indicate a change in magma supply rate for the volcano. This would correspond to the change in eruption frequency and the appearance of xenocrystic olivine previously discussed in Part I. This change in effusion rate for Ruiz supports our assertion that the volcano has undergone a fundamental change in activity beginning with eruption R4. Finally, the curves of Figure 30 suggest that, in general, one might expect more frequent eruptions of Ruiz than may have been typical for this volcano as recent as eruption R2, and that these eruptions will probably be of magnitudes less than or equal to the eruptions R4 and R2. If eruptions continue to occur after repose periods similar to historic times, smaller volumes similar to the deposits of R1 and R0 might be reasonably expected, barring
Figure 30. Plot of cumulative volume erupted versus time for the main Ruiz sequence (R6 excluded).
any major inflation of the edifice.

Comparison of individual eruption characteristics reveals that the 1985 eruption produces the greatest estimated column height, but the smallest estimated volume. It should be noted that a larger previous estimate of 0.039 km$^3$ has been published for the 1985 deposit (Naranjo et al., 1986), and that this estimate is based on an extrapolated volume derived by increasing the calculated volume within the 1mm isopach by 25% to account for the volume of the fines. This volume estimate has the advantage of thickness measurements which were taken almost immediately after the eruption, and produces an eruption duration of approximately 20 minutes for the 1985 event, which is probably more representative of the actual eruption than our calculated duration. Either volume estimate is approximately an order of magnitude smaller than the largest volume eruptions (R8, R7, R4, and R2). Based on our calculations of volume, the total volume of R8 is approximately 15 times greater than that of R0 (1985), yet column heights are modeled to be nearly equal.

Apparent wind velocity is much greater for R0 (21 m/s) than for the other eruptions. This may be due to the heavy rainstorms reported around the region of the volcano on the night of the eruption. The results of the wind influence can be seen in the distribution pattern of R0, which is much more confined than other deposits, occurring along a narrow corridor down the valley of the Azufrado River valley (Appendix 3). In this light, it can be said that the distribution pattern of the 1985 event is unique among the series of eruptions we have studied here. There is good agreement among the isopach and isopleth maps of previous eruptions that all the pre-1985 deposits have either been distributed in nearly circular patterns around the volcano (i.e. low cross-wind velocities) e.g. eruptions R7 and R8, or slightly elongate patterns along an axis directed S-SW from the Arenas crater (R4, R5), a direction that is nearly directly opposite to the axis of dispersal of the 1985 eruption. The implications are that the 1985 event was unusual in terms of its dispersal pattern and that the much more voluminous events of the recent
past have been deposited in different areas and along very different axes from R0. The current ashfall hazard map for Ruiz depicts areas which coincide with the axis of dispersal of the 1985 eruption as being at greatest risk (Figure 31, Appendix 3). Interestingly, this map was finalized only one day before the eruption of 13 November, 1985. Not only did this map outline the danger of mudflows at Armero, it seemingly predicted the distribution pattern of the 1985 deposit, a distribution pattern that is not representative of the recent eruptive history of the volcano. Conversations with scientists on the scene of the developing situation prior to the November 1985 eruption confirm that it is likely that Cerro Bravo deposits (the thickest and most prominent layers on that sector of the volcano) were incorrectly attributed to Ruiz. It should be noted that the Ruiz hazard map was compiled, remarkably, in the short time span (approximately one month) between the explosion of 11 September and the eruption of 13 November. The nearly perfect match between the incorrect perception that the Ruiz deposits are thickest on the NE sector of the volcano and the actual dispersal axis of the 1985 deposit has resulted in a general belief among some of the population and public officials near the volcano that all future eruptions will be similarly restricted to the Azufrado River Valley. In order to convey a sense of where the tephra deposits have accumulated, a cumulative ashfall map for the main Ruiz sequence of deposits was constructed (Figure 31). Because only proximal deposit isopachs were measurable, and because only several centimeters of ash, especially when wet, can begin to collapse structures, it was necessary to extrapolate the individual isopach maps to smaller thicknesses to estimate their distributions. Each isopach map in Appendix 2 was extrapolated out to the 2 cm isopach along the four principal directions (N, S, E, W) by means of the line formed by plotting the distance from the crater along the four directions of known isopachs versus the ln(thickness of those isopachs), and extrapolating the location of smaller isopachs in each direction around the volcano. Isopach maps of each eruption were then placed on a 2.5 km square grid covering the Ruiz-Tolima complex and added
Figure 31. Cumulative accumulation isopach map for the main Ruiz sequence of deposits (R6 excluded). Also shown are lines illustrating current ashfall hazards at Ruiz as described by the published hazard map for the volcano. Heavy line: high ashfall risk, dotted line: moderate risk. Isopachs are in centimeters.
successively to determine areas of maximum accumulation. Figure 31 demonstrates that the tephra from eruptions R8-R0 has accumulated in a nearly circular pattern around the volcano that is slightly elongate along an axis directed S-SW from the Arenas crater. This direction coincides with the dominant dispersal direction for the airfall deposits of Cerro Bravo volcano (Lescinsky, 1990), and may reflect the upper-level wind regime for the region. Because surficial winds at Ruiz are predominantly from the E-SE, it is typical for small eruptions including the explosion of 11 September, 1985, the eruption of 1 September, 1989, and numerous other post-1985 ash eruptions to be dispersed towards the W-NW from the summit, in the general direction of Manizales, about 90° west of the current hazard zone axis. It is our recommendation that the ashfall hazard map for Ruiz should be revised to reflect what is now known about the eruptive history of the volcano and how the current map was prepared. Naturally, any modifications to the vent morphology could play a role in controlling the eruption column behavior, and must be included in any evolving hazard assessment situation.

CONCLUSIONS

By all accounts, the Ruiz deposits represent small volumes of material, yet the eruptions involve significant column heights that are plinian in nature. These results raise obvious questions about the possible minimum volume limits for true, sustained plinian eruption columns which we will not address here. More importantly, this says something about the nature of the eruptions at Ruiz. We feel that these eruptions have been intense, short-lived gas bursts involving a small, upper-level magma chamber that is fed from below by a larger body of crystallizing magma related to the caldera-scale ancestral Ruiz. While magma mixing is evident in the most recent eruptions and may be playing an increasing role in these eruptions, we find earlier eruptions show little evidence of mixing and we consider periodic gas overpressures to be the driving force behind all the eruptions. The increase in eruption frequency, effusion rate, and
the appearance of xenocrystic olivine beginning with eruption R4 signals a fundamental change in the behavior of the volcano, possibly due to the opening of a more efficient conduit for the transfer of blebs of magma and gas rising from below into the upper chamber. The continuing, non-eruptive emission large amounts of SO_2 six years after the 1985 event supports the idea of a large crystallizing magma body at depth, and suggests a conduit that is relatively open to the Arenas crater at present. We now believe that another crater at Ruiz, La Olleta, has been active in the recent past, and that this conduit may be related to a separate magma source or domain common to other caldera-scale features of the volcano.

By putting the 1985 eruption into a frame of reference against the backdrop of what we now know about the petrology and eruptive characteristics of the earlier deposits, we can now characterize this eruption as unique in many respects. First, the tephra shows the greatest amount of petrologic diversity and influence from a more basic source which is not represented within the deposit. Secondly, the column height and hence, dispersive power of this eruption was probably greater than the any of the previous eruptions studied here, but the volume erupted was one of the smallest, possibly as a result of the increased eruption frequency during historic times. Finally, the distribution of the 1985 deposit is not representative of the prior, more voluminous eruptions, and current ashfall hazards at Ruiz should be reevaluated.
REFERENCES


APPENDIX 1. MICROPROBE STANDARD CALIBRATION

To assure the precision of matrix glass analyses, Smithsonian Rhyolite glass # VG-568 (Smithsonian reference USNM #72854) was re-analysed as an unknown throughout the procedure. Results of these six test points are presented in Table A, along with the mean, standard deviation, and the published wet chemical analysis for this glass. Test values for Ca and K are more than one standard deviation below the published values. To evaluate the effect of these lower values on graphical data for the ternary diagrams used to estimate water content of magmas and pressure, the mean, along with the upper and lower limit of the test point values from the table were plotted along with the published values (a total of four points) on a plag-hyp-q+or ternary diagram (Figure A). The four points are virtually indistinguishable, but the published values plot essentially at the center, with nearly all variation due to the slight differences in SiO₂ content between the test points and the published value. For the geohygrometer of Merzbacher and Eggler (1984), the effect of our analytical bias is minimal, much less than the reported 1 percent sensitivity of the method.
<table>
<thead>
<tr>
<th>Microprobe test point values</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>Fe2O3</th>
<th>FeO</th>
<th>FeO*</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>Na2O*</th>
<th>K2O</th>
<th>P2O5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>76.87</td>
<td>11.86</td>
<td></td>
<td>1.14</td>
<td></td>
<td></td>
<td>0.43</td>
<td>2.64</td>
<td>3.78</td>
<td>4.42</td>
<td>98.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.36</td>
<td>11.71</td>
<td></td>
<td>1.02</td>
<td></td>
<td></td>
<td>0.43</td>
<td>2.59</td>
<td>3.72</td>
<td>4.42</td>
<td>97.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.74</td>
<td>11.83</td>
<td></td>
<td>0.88</td>
<td></td>
<td></td>
<td>0.36</td>
<td>2.54</td>
<td>3.83</td>
<td>4.44</td>
<td>98.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.34</td>
<td>11.84</td>
<td></td>
<td>1.03</td>
<td></td>
<td></td>
<td>0.45</td>
<td>2.56</td>
<td>3.77</td>
<td>4.42</td>
<td>0.01</td>
<td>97.85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77.35</td>
<td>12.26</td>
<td></td>
<td>1.14</td>
<td></td>
<td></td>
<td>0.42</td>
<td>2.51</td>
<td>3.81</td>
<td>4.50</td>
<td>0.01</td>
<td>99.49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.97</td>
<td>11.91</td>
<td></td>
<td>1.11</td>
<td></td>
<td></td>
<td>0.43</td>
<td>2.46</td>
<td>3.73</td>
<td>4.43</td>
<td>0.02</td>
<td>98.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>76.77</td>
<td></td>
<td>1.05</td>
<td></td>
<td></td>
<td>0.42</td>
<td>2.55</td>
<td>3.77</td>
<td>4.44</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.38</td>
<td>0.19</td>
<td></td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Published wet chemical values</td>
<td>76.71</td>
<td>0.12</td>
<td>12.06</td>
<td>0.48</td>
<td>1.23</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>0.50</td>
<td>3.75</td>
<td>4.89</td>
<td>0.01</td>
<td>99.56</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A. FeO* denotes total iron
Na2O* denotes corrected sodium (see text)
Figure A.
APPENDIX 2. WHOLE ROCK DATA DISTRIBUTIONS

Appendix 2 contains the individual distributions of data from the individual references used to compile Figures 19 and 20. References coded as follows:

A. Melson et al. (1990)
B. Sigurdsson et al. (1990)
C. Gorgaud and Thouret (1990)
D. Vatin-Perignon et al. (1990)
E. This study
APPENDIX 3. ISOPACH, ISOPLETH, AND MEDIAN GRAINSIZE MAPS

(all data and contours in cm)
VITA

Rick Young was born in Sulphur, Louisiana in western Calcasieu Parish and graduated from Sulphur High School in 1973. After receiving an A.S. in Electronics Technology from McNeese State University in Lake Charles, Louisiana in 1978, he was employed by Sulphur Cablevision and Cameron Telephone Company, before moving to California in 1980. He was employed by Varian Associates of Palo Alto as a microwave technician until the fall of 1982, when he returned to Louisiana to enter L.S.U. in Baton Rouge. He received a B.S. in Geology in May of 1987, and a M.S in August of 1991. He is currently employed as a research associate in the Department of Geology and Geophysics at L.S.U.
Candidate: Richard Henry Young

Major Field: Geology

Title of Thesis: Eruption Dynamics and Petrology of the Most Recent Eruptions of Nevado del Ruiz Volcano, Colombia, South America

Date of Examination: June 28, 1991